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DEVELOPMENT OF STANDARD FIRE TEST RATING SYSTEMS FOR SHELTER COMPONENTS

Final Report

by

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IITRI N6061
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FOREWORD

This is the final report on Multi-Task Contract No. OCD-PS-64-50, Subtask 1132A (IITRI Project No. N6061). The OCD task coordinator was Mr. John Christian. The contract period was September 30, 1963 to February 20, 1966.

Respectfully submitted,

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ABSTRACT

In this study fire tests for the purpose of rating structural components of blast shelters and fallout shelters are considered. Existing fire test procedures for building construction and materials, door assemblies, and window assemblies are analyzed to determine how results from these tests may be applied toward the development of a system for rating shelter components.

Shelter component performance requirements in regard to heat transmission, smoke and toxic gas build-up in shelter areas, and fire spread and structural collapse are described.

Fire exposures for the rating of shelter components are described and classified according to their characteristic modes of heat transfer. The sources of these exposures, described as exposures from fire within the shelter building, from fire in individual nearby buildings, from mass fire, and from debris fire, are analyzed and interim data presented on exposure severity. A useful concept for the comparison of fire exposures, based upon their effects on each type of component, is defined.

The approach used in existing fire test methods was found to be compatible with shelter component testing, provided furnaces are equipped with gas collection systems. Problems involving restraint of test specimens, encountered in existing test methods, persist in shelter component testing. An interim

approach for the modification of existing restraining methods is recommended. Suggestions are made regarding the method of reporting results of shelter component tests.

Verification experiments are described, the completion of which would provide the additional input data needed for the fire test rating of shelter components.

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A	Compartment floor area
A_f	Fuel surface area
A_w	Window area
C	Fraction of total weight of fuel burned
h	Height of the hot gas column
h_w	Window height
I	Intensity of radiation
I_{max}	Maximum radiation intensity
K	Constant in Eq. 7
k	Flow coefficient, Eq. 3 Constant = 1.5, Eq. 10
m	Time constant, Eq. 18
P_a	Atmospheric pressure
p_w	Velocity head due to wind
P_w	Theoretical absolute pressure due to wind within an enclosure on the windward side of a building
ΔP	Pressure difference
ΔP_b	Theoretical pressure difference across an enclosure due to buoyancy of hot gases
ΔP_t	Sum of all pressure differences
ΔP_w	Pressure difference due to wind effects
Q	Volume flow rate, or volumetric rate of influx of contaminating gas
R	Burning rate - lb/min
R_f	Fuel surface controlled burning rate
R_v	Ventilation controlled burning rate without wind

LIST OF SYMBOLS (Cont.)

T	Absolute temperature
T_a	Absolute ambient temperature
T_g	Average enclosure absolute gas temperature
T_i	Initial absolute temperature encompassing a fire
T_{max}	Maximum absolute temperature attained by a fire
$T°$	Temperature parameter defined by the equation

$$T° = \frac{T - T_i}{T_{max} - T_i} \times 100$$

t	Temperature, °F
t_{max}	Maximum temperature, °F
t_f	Thickness of fuel elements
V	Shelter volume
V_w	Wind velocity
W	Total weight of fuel in compartment
w	Compartment fire load per unit area
X_{co}	Carbon monoxide concentration
X_f	Concentration of contaminating gas on the fire side of barrier
X_s	Concentration of contaminating gas in the shelter
$_f$	Specific weight of fuel
ε	Emittance
ρ	Density
σ	Stefan-Baltzmann constant

LIST OF SYMBOLS (Cont.)

τ	Time
τ_c	Critical exposure time to reach an unsafe carbon monoxide concentration
τ_r	Residual burning time

I. INTRODUCTION

An essential area of civil defense is the establishment of shelters in which large portions of the civilian population can be interned for the duration of dangerous nuclear radiation levels following an attack. Without doubt, fires will follow a nuclear attack. Therefore, it is important to provide for the integrity of shelters exposed not only to nuclear blast or fallout, but also to the effects of fire.

In this study, shelter components are defined as any parts of the shelter or shelter building which act as barriers serving to obstruct the passage of fire, heat, and fire gases, as well as to provide resistance to structural collapse. Shelter contents are excluded from treatment as shelter components.

Two basic types of shelters are considered, blast shelters and fallout shelters, and these differ somewhat in fire-resistance requirements. Blast shelters are defined in this study as structures designed primarily for use as shelters, since these generally provide considerable resistance to blast damage. Buildings chosen for secondary use as shelters are termed fallout shelters.

Existing methods for fire rating of building components, because they are based on peacetime situations, presuppose that evacuation of the building is possible, that organized fire fighting can be initiated without impediment, and that an adequate water supply exists. Under attack conditions, the shelter building cannot be evacuated, public fire fighting

cannot be expected, and fire fighting by shelter occupants will be severely limited by the existence of radioactive fallout as well as by a shortage of water. Clearly, the fire resistance now required of building components for peacetime usage will in many cases be inadequate for protection of shelter occupants. It is the purpose of this study to develop fire-testing procedures for judging shelter components. The objectives of this program are as follows:

(1) to develop a system for rating structural components in their capacity to protect the shelter from exposure to the anticipated fire intensity.

(2) to plan experimental programs to verify input data for recommended fire test procedures and criteria related to the rating of shelter components.

The approach used for this study was to analyze existing fire test procedures and to determine (1) their relation to actual fire conditions, (2) the extent to which these tests may be applied toward the rating of shelter components, and (3) how existing fire test methods can be extended to include the additional test parameters needed for shelter components.

For both shelter types, the ability of existing fire test procedures to measure the performance of shelter components has been examined, and criteria for defining component failures have been established. New test standards and procedures are defined wherever existing methods are inadequate.

II. EXISTING FIRE RESISTANCE TESTING

A. General

The approach used for this study was to analyze existing fire test procedures and data to determine how results from these tests may be applied toward the development of a system for rating shelter components. For this purpose, the following standard fire tests were examined in detail:

1. Standard Methods of Fire Tests of Building Construction and Materials, ASTM designation E-119, 1963 Book of ASTM Standards, Part 5.
2. Standard Methods of Fire Tests of Door Assemblies, ASTM designation E-152, 1963 Book of ASTM Standards, Part 5.
3. Tentative Methods for Fire Tests of Window Assemblies, ASTM designation E-163-60T, 1963 Book of ASTM Standards, Part 5.

The scope of each test is quoted in Section C to introduce the test for discussion .

In general, proper applications of test ratings are intended to:

1. Preserve life in a peacetime fire by providing time for safe exit from a building suffering an interior fire.
2. Prevent conflagrations in built-up areas.
3. Provide time for fire departments to save individual properties.

4. Provide a basis for fire insurance rating by estimating the extent of damage.

Notable among the provisions in the scope of each test is that the results "shall not be construed as determining suitability for use after exposure to fire." This intent may be applied to peacetime structures. However, occupants may be interned in shelters before, during, and after fire exposure. To maintain the integrity of a shelter, components must perform their functions as well after fire exposure, as before. This requirement implies that the fire exposure rating associated with any given component must describe its behavior during fire exposure, and after fire exposure, for various levels of exposure severity.

B. Standardized Fire Exposure

The ASTM methods of fire tests prescribe a standard exposing fire of controlled extent and severity, defined by a specific temperature-time relationship, which can be approximated by the following equations:

Above a base line of 68°F, the portion of the curve included between the times $o \leq \tau \leq 120$ minutes is given by the equation reported by Salzberg et al. (1) modified for the condition $\tau = 0$ at $T_{68} = 0$:

$$T_{68} = 435 \log_{10} 105 (\tau - 4) \qquad (1)$$

where

T_{68} = temperature (°F) above the base line of 68°F.

τ = Time, minutes.

Above a base line of 68°F, the portion of the curve after $\tau = 120$ minutes is a straight line, with a slope of 1.25°F per minute, and is given by the equation

$$T_{68} = 1.25\,\tau + 1632 \qquad (2)$$

The standard time-temperature curve described above is shown in Fig. 1 as taken from Ingberg (2). Superimposed on the same graph, Ingberg shows the average time-temperature curve from a full-scale experimental building fire, together with cooling curves obtained from temperature measurements of a fire test furnace. The average curve for the building fire test agrees well with the general shape of the curves shown in Figs. 3 and 4.

According to Ingberg (2), the area under the time-temperature curve, above an appropriate base line, may be used as an approximate measure of severity of fire exposure. Two fires, having different time-temperature curves, are then said to be equally severe if this area is the same for both. Ingberg points out further that, in making such comparisons, the minimum temperature that need be considered as an exposing temperature must be taken into account. That author suggests base line temperatures of 150°C (302°F) and 300°C (572°F), for exposure of combustible and non-combustible materials, respectively. In making a comparison of areas under two different time-temperature curves, Ingberg also includes the cooling portion of the curves for both fires. Accordingly, the severity of any fire can be expressed in terms of a time of exposure

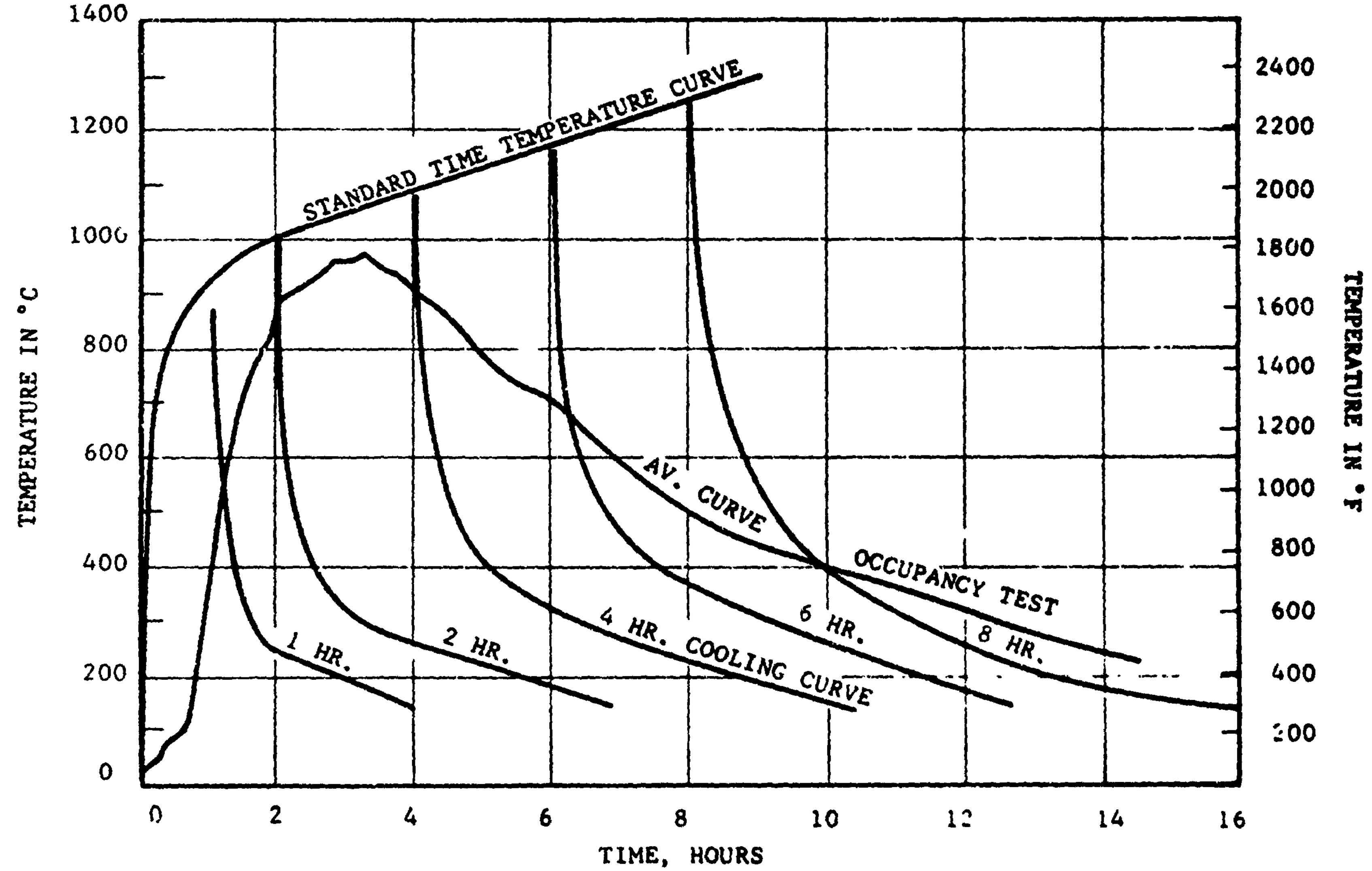


Fig. 1 STANDARD TIME TEMPERATURE CURVE USED IN FURNACE FIRE TESTS, COOLING CURVES, AND CURVE REPRESENTING THE TEMPERATURES IN A TYPICAL OCCUPANCY TEST

to a fire having the standard time-temperature relation.

This method apparently stems from consideration of simple heat transfer. However, since the component loses heat by radiation and also the properties of the component may change with time (because of such things as thermal decomposition, moisture loss or structural cracking) there seems to be a question regarding the definition of fire severity in terms of area under the time-temperature curve, particularly where the temperature levels may differ significantly. In fact, the term "temperature level" may be in itself an inadequate description of the severity of exposure.

The fundamental approach which must be used to compare one fire exposure with another is based upon their effects on each type of test specimen. For this purpose, it may be stated that equivalent fire exposures produce identical time-variant temperature distributions within identical building components. This topic is discussed further in Chapter IV of this report.

C. Standard Methods of Fire Tests

1. Building Construction and Materials, ASTM E119
Scope of ASTM E119

"(a) These methods of fire tests are applicable to assemblies of masonry units and to composite assemblies of structural materials for buildings, including bearing and other walls and partitions, columns, girders, beams, slabs and composite slab and beam assemblies for floors and roofs.

They are also applicable to other assemblies and structural units that constitute permanent integral parts of a finished building.

(b) It is the intent that classifications shall register performance during the period of exposure and shall not be construed as having determined suitability for use after fire exposure."

According to Harmathy (3), "The practical measure of the fire enduring quality of a construction is the 'fire resistance', the time for which the construction functions as a fire barrier in a specified sense, when subjected to a standard fire endurance test." Standard fire tests are designed to measure the fire resistance of building construction materials and assemblies when subjected to a standardized fire exposure. Performance is defined as the period of resistance to standard exposure elapsing before the first critical point in behavior is observed. Results of tests are expressed in time periods, such as "2-hr.," "1/2-hr.," "6-hr.," etc. The test does not provide absolute values of fire resistance. As stated by Bletzacker (4),"---, the test gives a measure or index by which to compare one construction system with all other construction systems under one standard set of fire conditions." Bletzacker argues that the test need not be related to any actual building or any real fire, if two essential elements of the test method are specified, i.e., a standardized fire exposure, and a test specimen of suitable size, representative

of the construction system under consideration. The standardized fire exposure used in these test methods was described in a previous section of this report. Other test conditions, including conditions of acceptance, are summarized in Table I, supplemented by appropriate notes.

Test specimens are representative sections of a building constructed in test frames. The specimen size and area exposed to fire varies with the part of the building being tested, as indicated in Column 2 of Table I. Materials and workmanship are intended to be of the same quality used in the construction of buildings. The sample is aged, if necessary, so that a large proportion of the final strength of the material has been attained before the test.

Two kinds of fire tests are conducted, the fire endurance test and the hose stream test. For both tests, the specimen in its frame is mounted in the test furnace. A wall or partition specimen forms one wall of a vertical furnace and is exposed to fire on one side. A floor or roof specimen forms the roof of a horizontal furnace and is exposed to fire on the underside. A column specimen is mounted at the center of a cylindrical furnace and is surrounded by the test fire. The fire endurance test on the specimen with its applied load, if any, is continued until failure occurs, or until the specimen has withstood the test conditions for the period of time specified for the type of construction. For the hose stream test, a duplicate specimen is subjected to a fire exposure for a

TABLE I

SUMMARY OF STANDARD METHODS OF FIRE TESTS OF BUILDING CONSTRUCTION AND MATERIALS ASTM E 119

	Size of Specimen		Kinds of Tests Required		Load Carried During Tests		Restraint				Conditions of Acceptance Within the Intent of Each Kind of Test					
															Transmission of Heat	
															To Protected Steel	
Structural Component Under Test	Area Exposed to Fire(Ft^2)	Minimum Dimension (Ft)	Fire Endurance Test	Fire And Hose Stream Test	Yes (See Note 1)	Dead Load Only	None	Loaded Edges Only	All Four Edges	(See Note 3)	Sustained Applied Load	No Passage of Flame or Gases Hot Enough to Ignite Cotton Waste	No Passage of Flame or Ignition of Material Protected	Average Temperature Rise(°F) Unexposed Side of Specimen	Average Temp. Rise (°F)	Max. Temp. Rise (°F) At Any Measured Point
Tests of Bearing Walls and Partitions	100	9	X	X	X (See Note 2)			X			X	X		250 (See Note 6)		
Tests of Non-Bearing Walls and Partitions	100	9	X	X		X			X			X		250 (See Note 6)		
Tests of Columns		9	X		X			X			X					
Alternate Test of Protection For Structural Steel Columns	Full Length of All Sides	8	X			X				X					1000	1200
Tests of Floors and Roofs	180	12	X		X			X			X	X		250 (See Note 6)		
Alternate Test of Protection For Solid Structural Steel Beams and Girders		12	X			X				X					1000	1200
Tests of Ceiling Constructions	180	12	X			X			X				X	250 (See Note 4a)	1200 (See Note 4b)	
Tests of Protection For Combustible Framing, or For Combustible Facings On The Unexposed Sides of Walls, Partitions And Floors	100 (Wall) 180 (Floor)	9 12	X			X	X						X	250 (See Note 5)		

NOTES FOR TABLE I

1. The members shall be loaded in a manner calculated to develop theoretically, as nearly as practicable, the working stresses contemplated by the design.

2. After cooling, but within 72 hours after completion of the fire and hose stream test, the specimen shall sustain the dead load of the test construction, plus twice the load applied during the test.

3. The applied protection materials shall be restrained against longitudinal temperature expansion greater than that of the steel.

4. (a) The temperature increase of combustible material either in contact with the ceiling, or adjacent to the ceiling, shall not exceed 250°F.

   (b) With no combustible material above the ceiling construction, the average temperature measured on the surface of the main structural supporting members shall not exceed 1200°F., and the average temperature of the top and bottom of the beams, when used, shall not exceed 1000°F.

5. Temperatures at contact with protected structural members or facings of the test panel shall not exceed 250°F.; for members closely embedded on three sides in masonry, concrete or other incombustible materials the permissible temperature rise may be 325°F.

6. Where the conditions of acceptance place a limitation on the rise of temperature of the unexposed surface, the temperature end point of the fire endurance period shall be determined by the average of the measurements taken at individual points; except that if a temperature rise 30 per cent in excess of the specified limit occurs at any one of these points, the remainder shall be ignored and the fire endurance period judged as ended.

period equal to one-half of that indicated as the resistance period in the fire endurance test, but not for more than one hour; immediately after this exposure, the specimen is removed from the furnace and subjected to the impact, erosion, and cooling effects of a hose stream directed at its exposed side. The water stream characteristics, distance and duration of application are specified in the text of the tests. As indicated in Column 3 of Table I, the fire endurance test is required for all kinds of construction; the fire and hose stream test is required for walls and partitions having a fire resistance of one hour or more.

Loads applied to test specimens during fire tests are indicated in Column 4 of Table I. The kinds of restraint prescribed for specimens under test are shown in Column 5. Within the intent of each kind of test (fire endurance or hose stream tests) the conditions of acceptance are outlined in Column 6. For details of the test requirements, the reader is referred to the full text of the standard method of tests.

2. Door Assemblies, ASTM E152

Scope of ASTM E152:

"(a) These methods of fire test are applicable to door assemblies of various materials and types of construction, for use in wall openings to retard the passage of fire.

(b) Tests made in conformity with these test methods will register performance during the test exposure; but such tests shall not be construed as determining suitability for use after exposure to fire.

(c) It is the intent that tests made in conformity with these test methods will develop data to enable regulatory bodies to determine the suitability of door assemblies for use in locations where fire resistance of a specified duration is required."

Fire tests of door assemblies consist of a fire endurance test, followed immediately by a hose stream test. A door assembly, including frame and hardware, is installed within a masonry wall constructed in a rigid steel frame. The masonry wall is restrained on all four edges by the frame. After proper ageing, the test assembly is mounted on a wall furnace and subjected to the standardized fire exposure described in Part B of Chapter II. During the fire endurance test, the pressure in the furnace chamber is maintained as nearly equal to the atmospheric pressure as possible. The fire endurance test is continued until the exposure period of the desired classification or rating of the door assembly is reached, unless the conditions of acceptance are exceeded in a shorter period. The performance of the door assembly is reported under the desired exposure period chosen from the following:

20 min., 30 min., 3/4hr., 1 hr., 1 1/2 hr. or 3 hr. Temperature measurements of the unexposed side of the test assembly are reported, if determined. Regarding criteria for acceptance, the integrity of the door assembly during the fire endurance and hose stream tests is the prime consideration; limitations are set for the movement of the door from its original position or out of the frame. For details, the reader is referred to the full text of the standard method of tests.

3. Window Assemblies, ASTM E163

Scope of ASTM E163:

"(a) These methods of fire tests are applicable to window assemblies, including glass block and other light transmitting assemblies, for use in wall openings to retard the passage of fire.

(b) Tests made in conformity with these test methods will register performance during the test exposure and develop data to enable regulatory bodies to determine the suitability of window assemblies for use in wall openings where fire protection is required. Such tests shall not be construed as determining suitability of window assemblies for continued use after fire exposure."

Fire tests of window assemblies, including glass block, consist of a fire endurance test, followed immediately by a

hose stream test. The test assembly, not less than 100 ft.^{2}, with neither dimension less than 9 ft., is installed in a masonry or reinforced concrete frame constructed in a rigid steel frame. Latches and fasteners, other than hinges, are located on the unexposed side. The masonry or reinforced concrete frame is restrained on all four edges by the rigid steel frame. After proper ageing, the test assembly is mounted on a wall furnace and subjected to the standardized fire exposure described in Part B of Chapter II. During the fire endurance test, the pressure in the furnace chamber is maintained as nearly equal to the atmospheric pressure as possible. The fire endurance test is continued for 45 minutes (maximum furnace temperature 1650°F) unless the conditions of acceptance are exceeded in a shorter period. A window or glass block assembly is considered as meeting the requirements for acceptable performance when it remains in the opening during the fire endurance and hose stream tests. Limitations are set for the loosening or movement of an assembly from its original position. The edges of at least 80 percent of the individual glass lights must remain in position throughout the hose stream test. At least 90 percent of the glass blocks must not develop through-openings. The unexposed surface temperatures are not measured. For details, the reader is referred to the full text of the method of tests.

D. Review of Fire Resistance Test Reports

A number of reports on routine tests of structural fire

resistance (ASTM E119) by several organizations have been reviewed. These organizations are Underwriters Laboratories, Inc., The Engineering Experiment Station of the Ohio State University, the Fire Prevention Research Institute, Inc., the Underwriters Laboratory of Canada and the National Bureau of Standards. Each test is reported as an evaluation of one particular assembly, except for Bureau of Standard projects where test series are usually undertaken. Unfortunately, these NBS reports are few in number, particularly for combinations of materials in building assemblies. The results of testing are usually the property of the manufacturers of the structural assemblies. onsequently, the disclosure of information about components and procedures is minimized. Reports of failure and marginal performances are not available.

Since the conclusions formed could be erroneous, a study of specific results involving only the successful tests has not been undertaken. The value of these test reports derives from examination of the manner in which fire rating tests were implemented. In these tests, observations and measurements of material behavior were usually made during initial application of the load, throughout the fire exposure and following the hose stream test. Quantitative information reported included: 1) the physical description of the assembly and the loading applied, 2) temperatures of the furnace and of the exposed and unexposed sides of the assembly, and 3) the deflection of the

assembly. Also reported were qualitative observations of the surface characteristics of the sample, such as charring and color changes, cracking or spalling. Observed moisture release from concrete and plaster, and oxidation and erosion of steel members were recorded.

III. SHELTER COMPONENT PERFORMANCE REQUIREMENTS

Chapter II has described the present system for rating the fire resistance of building components. With the possible exception of the techniques for developing "equivalent exposures," the system quite adequately indicates the ability of various barriers to inhibit the direct spread of the fire. The passage of heat and flames are evaluated within this frame of reference (eventual spread of the active fire.)

While not necessarily requiring a different test method, the nuclear attack situation does imply additional performance requirements for the shelter components. These can be generally described as relating to retention of a habitable environment within the shelter space and are discussed in the following paragraphs.

A. Heat Transmission

1. Blast Shelters

In the present study, blast shelters are taken to be individual buildings constructed primarily for shelter use and exposures resulting only from fires external to these shelter buildings are treated. An important consideration in the design of certain shelters, particularly underground

shelters, is the removal of metabolic heat and moisture as well as heat from other sources, when the shelter must be completely closed. Often, heat transmission through the walls will be the only cooling mechanism and relatively small heating of the shelter by external fires might upset the heat balance, causing dangerous temperature levels to be reached inside. In other cases, mechanical cooling equipment may be provided which is capable of removing not only the heat generated within the shelter but also some additional heat transmitted to the shelter because of fire. In either case, the amount of heat which may be safely transmitted to the shelter over and above that which can be removed either by conduction or refrigeration will depend on the temperature and humidity already existing in the shelter. Clearly then, limitations on heat transmission by shelter components depend largely on the thermal design of the shelter. It is certain that rating of components cannot be made solely on the basis of temperature rise on the unexposed side, as is the case in present fire resistance rating procedures A maximum overall heating rate will have to be specified for a shelter and the fire resistance of shelter components will need to be such that this maximum is not exceeded.

2. Fallout Shelters

Existing buildings chosen for secondary use as shelters are termed fallout shelters. Fire exposure to a fallout shelter may arise from fire in non-shelter areas within the

shelter building as well as from fire in adjacent buildings. Heat transmission to a fallout shelter may occur by conduction through the floor, walls and ceiling from fire in non-shelter areas, by thermal radiation, and by convection of heated gases through openings. In this case too, it is certain that rating of components cannot be made solely on the basis of temperature rise on the unexposed side. Because of exterior wall openings, some fallout shelters may not be as sensitive as blast shelters to metabolic heat of the occupants. However, these same exterior wall openings will permit fire gases and flame radiation to readily enter the shelter. Where conditions permit, heat transmission through a floor into a shelter may be avoided by occupants moving up (or down) one or more floors for the duration of the fire. In this case, the floor temperature on the unexposed side need only be limited to a value which would not result in fire spread. Where relocation of occupants within the shelter building is not feasible, the problem must be handled in a manner similar to blast shelters.

3. General Rating Considerations

To include the heating effects of fire exposure in his analysis of the thermal environment in a shelter, a designer must be able to determine the total quantity of heat entering the shelter for the duration of the fire. Since exposure fire conditions are transient, the rate of heat transfer per unit area of wall, floor, ceiling, door, or window varies

with time. For the same component surface area and fire exposure, the overall temperature rise in the shelter depends also upon the shelter volume, the quantity of heat generated within the shelter, as well as the total quantity of heat leaving the shelter. Heat transmission per se is not a requirement for rejection of a component, except as it contributes to shelter heating and to excess temperature rise on the unexposed surface. To avoid the generation of smoke, toxic and irritating gases, and possible ignition, certain coatings on the shelter side of a component may require a limitation of temperature rise on the unexposed side. Decomposition of the coatings may begin at a certain temperature rise, resulting in these undesirable effects.

Fire doors, glass blocks and wired glass in metal frame windows would, in general, permit a high rate of heat transmission per unit area. Some types of fire doors possess a limited resistance to heat transmission, while others may become red hot or deform sufficiently to permit the direct passage of flame from the fire side. Fire doors with wood cores will produce fingers of flame on the unexposed side as a result of ignition of decomposition products.

A description of the temperature on the unexposed side of each barrier will permit assessment of heat transmission to specific shelters. Direct radiant transmission can be treated by establishing the transmissivity of openings covered with wired glass or glass blocks. Direct passage of hot gases

can be assessed by the methods to be described in Section III B which follows.

B. Smoke and Toxic Gas Build-Up in Shelter Areas

The gases evolved as products of combustion during the course of a fire (referred to as fire gases) form a complex mixture. The constituents of this mixture depend on the fuel composition, on the degree of ventilation of the fire, and on other fire conditions. The composition can vary considerably from fire to fire, as well as from time to time during a given fire. Carbon monoxide is a constituent common to gases from fires involving carbonaceous fuels; and in the concentrations found in fire gases, carbon monoxide is a peril to life. While reduction of visibility and chemical irritation also constitute hazards to life, these effects are difficult to measure and, particularly in the case of chemical irritation, may vary greatly with each individual situation. Therefore, the flow rate of carbon monoxide through barriers into shelters appears to be the most definitive measure for rating shelter components.

To represent properly the conditions on the fire side of a barrier, a typical carbon monoxide concentration must be chosen for each class of fire exposure. Then for fire gases to flow into a shelter through cracks, porous materials, and other openings in barriers, a pressure difference must exist between the fire side and the shelter side. The rate of flow

varies with pressure difference according to an equation of the form,

$$Q = k\Delta P^{1/2} \qquad (3)$$

Q = volume flow rate, cubic feet per minute

ΔP = pressure difference, inches of water pressure above atmospheric pressure

k = flow coefficient

The buildup of smoke and toxic gas in the shelter area can be calculated in terms of the fire-generated gas concentration and the pressure-induced flow rate. The resulting shelter gas concentration can then be related to the levels of human tolerance. Consider the flow of a contaminating gas-air mixture (carbon monoxide for shelter-component rating) from adjacent burning areas into a shelter. If the pressure difference across the barrier remains constant, flow of the contaminating gas-air mixture into a shelter must displace an equal volume of shelter atmosphere. If mixing within the shelter is perfect and instantaneous, the time required to reach a given concentration X_s of contaminating gas can be calculated by the equation,

$$\tau = -\frac{V}{Q} \ln \left(1 - \frac{X_s}{X_f}\right) \qquad (4)$$

where

τ = time, minutes

V = shelter volume, cubic feet

Q = volumetric rate of influx of contaminating gas, cubic feet per minute

X_s = concentration of contaminating gas in the shelter, volume per cent

X_f = concentration of contaminating gas on the fire side, volume per cent

Expressed in terms of critical exposure tir $_c$) this relationship is:

$$\int_0^{\tau_c} X_s \, d\tau = X_f \left[\tau_c + \frac{V}{Q} \left\{ \exp(-\tau_c \, Q/V) - 1 \right\} \right] \quad (5)$$

The development of Eqs. 4 and 5 is treated in Appendix A.
In terms of exposure time for some critical effect to occur, various tolerance values of carbon monoxide concentration are reported in the literature.

Claudy (5) reports the following values for active firemen:

Carbon Monoxide Concentration (per cent) X_{co}	Fatal Exposure Time (minutes) τ_c
1.28	1 - 3
0.64	10 - 15
0.32	30 - 60
0.16	120

Haggard and Henderson (6) suggest the following relation by which fatal exposure to carbon monoxide can be predicted.

$$X_{co} \, \tau_c = 9 \quad (6)$$

Forbes et al. (7) present data which can be interpreted according to the equation

$$X_{co} \, \tau_c = K \quad (7)$$

where

K	EXTENT OF BODILY EXERTION
11.7	For persons at rest
7	For light activity
4.4	For light work
3.2	For heavy work

In view of the above information, the value of K = 9 given by Haggard and Henderson (Eq. 6) is suggested as a reasonable representation of shelter conditions. It is somewhat more conservative than Claudy's representation in the longer periods of time. To represent changing carbon monoxide concentrations within a shelter, Eq. 6 can be rewritten in the following form where X_s has the same meaning as in Eq. 5:

$$\int_0^{\tau_c} X_s \, d\tau = 9 \qquad (8)$$

The time required for reduction of the carbon monoxide concentration in the shelter after the fire exposure is also important. Depending upon the particular geometry of each situation and the extent of the debris fire still existing, the time required for return to uncontaminated air may be quite variable. It seems reasonable to assume that properly selected procedures by the shelter occupants can reduce carbon monoxide concentration at least as fast as it was built up. Thus, the carbon monoxide exposure during the active fire can be assumed to be one half of

the total exposure and

$$X_f \left[\tau_c + \frac{V}{Q} \left(\exp\left(-\tau_c\, Q/V\right) - 1 \right) \right] = 4\ 5 \qquad (9)$$

where

τ_c = the critical time of exposure to active fire conditions, minutes.

The nature of the above expression requires that the criteria of failure be related not only to the fire exposure and to the particular shelter component, but to the volume of the shelter as well. Thus, an adequate carbon monoxide barrier for a large shelter may not suffice for a smaller shelter. In practice, the shelter volume can probably be expressed in terms of shelter capacity in number of occupants.

C. <u>Fire Spread</u>

Fire spread between compartments separated by a barrier can occur in two ways:

1. The temperature developed on the unexposed side of the barrier may reach a value sufficient either to cause the ignition of combustible material in contact with the barrier; or, by thermal radiation, to cause the ignition of combustible material some distance away from the barrier.
2. During the course of the fire, the barrier may rupture to form a crack large enough to allow the passage of flame or gases hot enough to

cause the ignition of combustible material in the vicinity of or in contact with the unexposed side of the barrier.

In regard to the first mode of fire spread, the maximum safe temperature on the unexposed side of a barrier depends upon the kind of material stored in the vicinity of the barrier, how it is stored and the duration of exposure. According to Simms (8), the spontaneous ignition of cellulosic materials occurs when the fuel surface temperature reaches about 500°C (932°F). In the presence of air, the pyrolysis of organic fuels, including cellulosic materials, results in exothermic chemical reactions. Therefore, the fuel surface temperature rise sufficient for ignition, may occur partly as a result of heat transfer from an outside source and partly due to exothermic chemical reactions. If cellulosic materials are stored in a compact manner and in contact with a wall or floor so as to conserve heat, self-ignition is conceivable. While the 250°F average temperature rise (325°F maximum) on the unexposed side of a barrier is used as an end point in standard fire endurance tests, it is determined by measuring the temperature under an asbestos pad, with the remainder of the wall or floor surface subject to cooling. If heat loss is restricted by combustible insulating materials, the temperature attained by the unexposed surface of a barrier or adjacent material may be quite different than in the standard test. It may be necessary to prescribe a spacing of storage from walls and floors to avoid possible

fire spread into a shelter. Also, even without ignition, the generation of decomposition products in a closed shelter cannot be tolerated. Experiments designed to examine this subject and to establish criteria to handle the problem are described in Chapter VI.

In regard to fire spread, conventional fire doors are inherently the weakest part of a fire barrier. This is not limited to shelter components, but is recognized in general fire protection practice. The fire door problem has been discussed briefly under Heat Transmission performance requirements of shelter components. Storage of materials well away from fire doors, as well as the use of double fire-door protection, will help to overcome some problems. It is likely that fire doors will fail due to excessive gas flow prior to reaching the fire spread limit.

D. Structural Collapse

The existence of a habitable environment within a shelter is impaired if for any reason one or more of its components should collapse. It is well known that the exposure to fire of building components will bring about changes which in time may result in collapse. Therefore, the integrity of shelter structures demands that the fire exposure not reduce component strength below that needed to support the imposed load. Under ordinary structural conditions a floor or roof must support itself, as well as the building equipment and contents resting on it; a column or

bearing wall must support floor and roof loads; a nonbearing wall and partition need only support itself. When a building is exposed to fire, its structural elements suffer changes in materials which result in loss of strength; weakening of certain components in a structure may result in a change in magnitude and direction of forces imposed on other components. For this reason, the required resistance to collapse of any particular component as a result of fire exposure depends upon its function in the structure. A component may be part of a shelter or a part of a building in which a shelter exists. In some cases, failure of a portion of a floor or roof assembly may not be as serious to the overall structure as failure of one column. A fire wall must have stability against collapse or overturning far in excess of that offered by types of construction which perform satisfactorily in fire tests alone. In the absence of any fire test for stability, it is necessary to establish specifications on the basis of experience and performance in actual fires in addition to an adequate fire test rating. The standard fire test, in acknowledging that a loss of strength may not bring immediate collapse, requires an overload on the member following the fire endurance test. This helps to preserve the safety factor for normal load increases which may be made in the future use of the structure, as well as for abnormal loads which may occur during fire exposure.

However, the standard methods of fire test specifically discourage interpretation of test results and building component classifications in terms of suitability for use after fire exposure. It is also true that, in a large proportion of cases, failure under the fire endurance test occurs not by collapse but as a result of excess temperature rise on the unexposed surface. Hence, little is known in these cases about the time to collapse due to fire exposure. While application of the standard fire endurance test procedures to shelter components is deemed satisfactory to determine collapse time, the hose stream test may be excluded.

IV. FIRE EXPOSURE TO SHELTERS

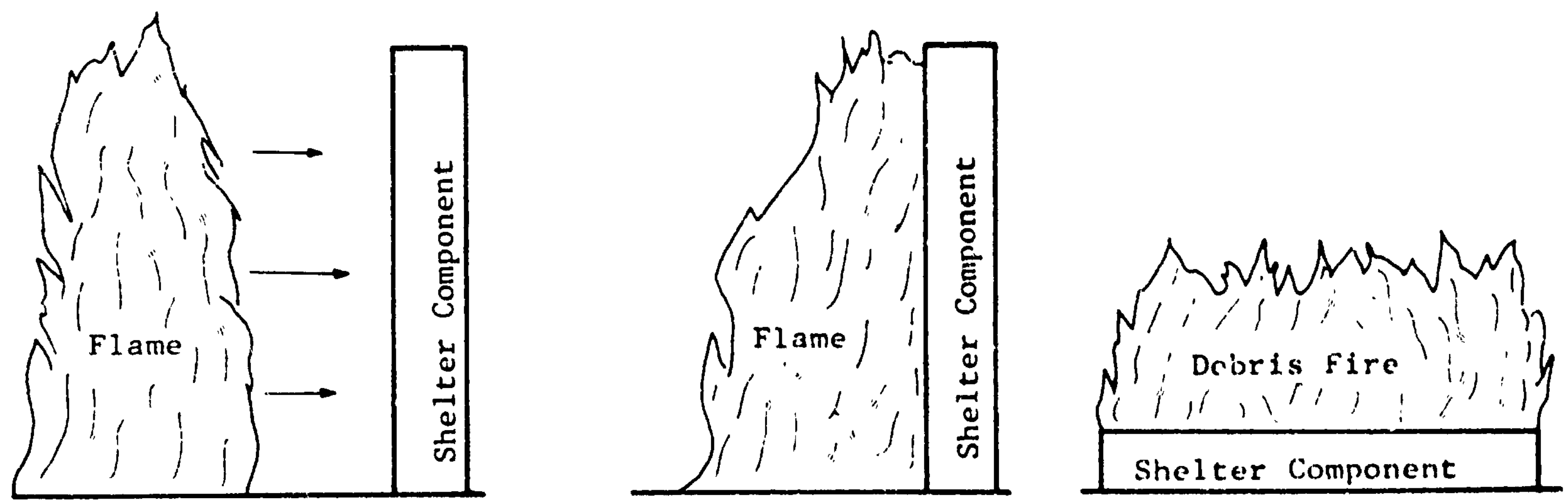
A. General

Fire exposures for the rating of shelter components are classified according to their characteristic modes of heat transfer, as shown in Fig. 2(a), (b) and (c):

(a) Distant Flame Exposure is characterized by transfer of heat to the shelter component due only to thermal radiation from a flame situated so as to avoid contact with the receiver.

(b) Impinging Flame Exposure is characterized by transfer of heat to the shelter component due to the combined effects of thermal radiation and convection from flame in contact with the receiver.

(c) Debris Fire Exposure is characterized by conductive transfer of heat to the shelter component from a mass of hot or burning materials resting on or adjacent to the receiver.



(a) Thermal Radiation

(b) Thermal Radiation and Convection

(c) Conduction

FIG. 2 MODES OF HEAT TRANSFER BY FIRE EXPOSURES TO SHELTER COMPONENTS

The sources of exposure described in this chapter may be outlined and classified as follows:

1. Exposure from fire within the shelter building- As the name implies, this type of fire exposure to shelter components consists of direct contact with flame as a result of fire in a portion of a building adjacent to a shelter in the same building. Accordingly, this type of exposure would be classified as "impinging flame exposure."

2. Exposure from fire in individual nearby buildings - This exposure is divided into two general types.

   a. The shelter building is separated from the exposing building by a fire wall. Where communicating openings between buildings are present, these are protected with standard fire doors. This type of exposure is similar to exposure from fire within the shelter building and would be classified as "impinging flame exposure."

   b. The shelter building is separated from the exposing building by an open space, perhaps the width of a street or an alley. Since heat transfer from this exposure would be due only to thermal radiation, it would classify as "distant flame exposure."

3. Exposure from mass fire - This exposure would result from the merging of several separate fires into a single fire involving a large number of buildings. A mass fire with a stationary front is called a "fire storm." A mass fire with a moving front is called a "conflagration." Depending upon location of the mass fire with respect to the shelter, this type of exposure may be classified as either "distant flame exposure" or "impinging flame exposure."

4. Exposure from debris fire - The intent here is to consider a fire involving the remains of a portion of an urban area resulting from a target response to a nuclear explosion. In addition to other exposure problems to be discussed, this type of exposure is characterized by conductive heat transfer. The term "debris fire exposure" is intended to be applied as a unique classification.

It is impractical to consider testing of shelter components by direct exposure to real fire conditions, such as a mass fire. Therefore, the effects of these exposures must be well enough understood to derive an equivalent shelter component rating by use of a practical fire exposure method.

Consider a non-combustible shelter component exposed to any source of heat. The ability of the component to endure the exposure until some predetermined test endpoint is reached depends upon the temperature distribution within the component

as a function of time. Test endpoints may include a limit on the maximum or average temperature on the unexposed side of the component; or a limit on component deformation resulting in a crack size and length sufficient to exceed a maximum flow rate of fire gases per unit wall area. At any instant, the temperature gradient from point-to-point within the component determines the distribution of forces due to thermal expansion responsible for component deformation. The temperature distribution as a function of time can, therefore, be used as a basis for comparison of the various types of fire exposures. For this purpose it may be stated that equivalent fire exposures produce identical time-variant temperature distributions within identical components, regardless of the mode (or modes) of heat transfer involved.

Comparison of fire exposures by means of the temperature distribution produced within components is a useful concept, but somewhat idealized with respect to application. Due to differences in materials and assembly, it is likely that so-called "identical" components will not develop exactly the same temperature distributions for identical exposures. Also, the actual test fire exposure can be expected to deviate from a desired specification because of variation in instrumentation and adjustments of test equipment. For this purpose it will be necessary to define the range of temperature distributions produced within similar components by similar fire exposures. This topic is given further treatment in Chapter VI on verification experiments.

B. Exposure From Fire Within the Shelter Building

1. Fire Behavior

Existing buildings chosen for secondary use as shelters are termed fallout shelters. In this case, the portions of a building meeting certain fallout protection requirements may be designated as shelter areas. The remaining portions of such a building are referred to as non-shelter areas. Therefore, fire from any cause in a non-shelter area may expose fallout shelter components. It is this type of exposure, classified as impinging flame exposure, which is described here.

A time-temperature curve (9) for a compartment fire is shown in Fig. 3. These data were obtained for a very small model and are not necessarily typical of building fires. However, the curve does show the important phases of a typical fire in a compartment, and is included here for illustrative purposes. After an initial growth period, flashover occurs (A on the curve) marking the time after which flame fills the compartment. The period of fully developed fire (A to B on the curve) is known also as "the period of maximum flaming". It is this portion of a fire which contributes most to the fire exposure of building components. The B - C portion of the curve represents the decay period of the fire.

A normalized fire time-temperature curve is described by Chandler et al. (10) and is given in Fig. 4. A curve of this type is derived from a real time-temperature curve by plotting the term

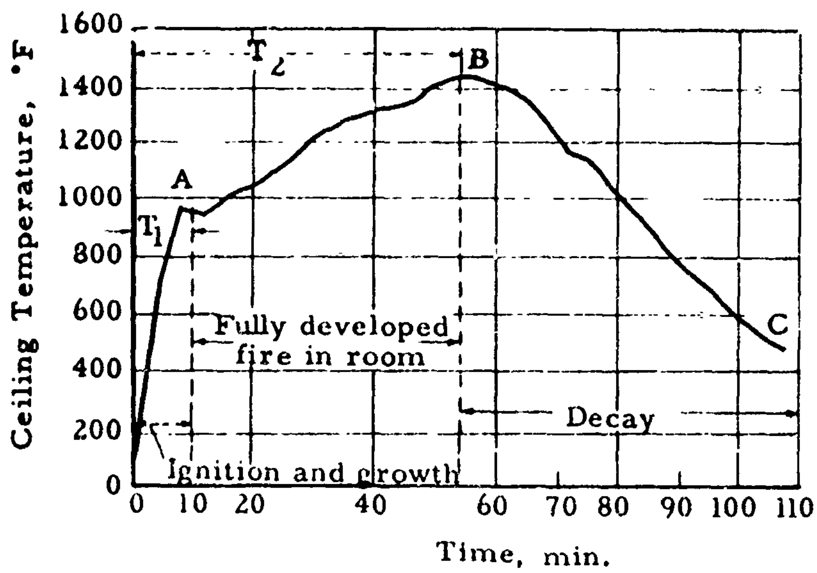


Fig. 3 TEMPERATURE-TIME RECORD FOR A TYPICAL FIRE (Small Scale)

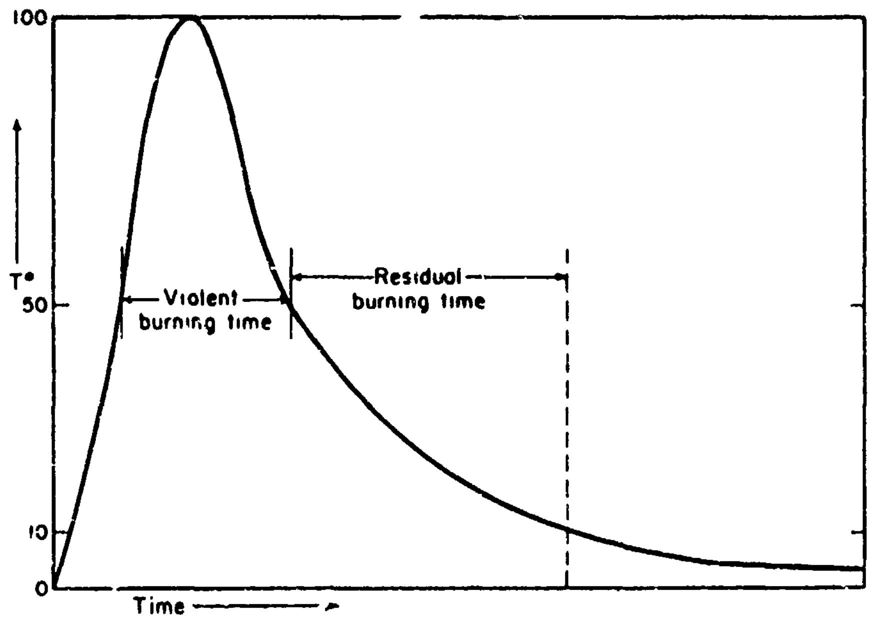


Fig. 4 DISTRIBUTION OF TEMPERATURE IN RELATION TO BURNING TIME. $\left(T^{o} = \frac{T - T_i}{T_{max} - T_i} \times 100\right)$

$$T^{o} = \frac{T - T_i}{T_{max} - T_i} \times 100$$

against the time τ, where T_{max} represents the maximum temperature attained by the fire, T_i is the initial or base temperature and T is the temperature at time τ. A normalized time-thermal radiation curve may be derived by a similar method. Chandler et al. define two regimes for the normalized curves as follows:

1. <u>Violet Burning Time</u>: the period in which (thermal) radiation (or temperature) exceeds 50 percent of the maximum value.
2. <u>Residual Burning Time:</u> the period after peak when (thermal) radiation (or temperature) is between 50 percent and 10 percent of the maximum value.

The violent burning time corresponds to the "period of maximum flaming"; also, the residual burning time corresponds to the "decay" period.

A fire is said to be ventilation controlled when the weight rate at which fuel is consumed is determined by the rate at which air is supplied for combustion. Consider a fire in a compartment with a window that is small compared to the size of the compartment. For negligible wind, the ventilation controlled burning rate R_v, may be calculated by an equation of the form:

$$R_v = k\ A_w\ h_w \qquad (10)$$

where

R_v = ventilation controlled burning rate without wind, lb/min

A_w = window area, ft.^{2}

h_w = window height, ft.

k = constant = 1.5 lb min^{-1} $\text{ft}^{5/2}$

This equation may be applied with satisfactory results for wind velocities not exceeding 15 ft/sec (10 mph) and for window areas not exceeding 15 percent of wall area, depending on the fire load in the compartment.

If a certain fraction, C, of the total fuel, W_f, burns during a time τ, the following relation applies:

$$\tau = C\frac{W}{R} = C\frac{w\,A}{R} \qquad (11)$$

where

τ = fire time, or fire duration, minutes

W = total weight of fuel in compartment, lbs.

w = fire load in compartment, lb/ft^2

A = compartment floor area, ft^2

R = burning rate, lb/min

C = fraction of total weight of fuel burned

Approximately 50 percent of the total weight of fuel in the compartment is burned during the period of maximum flaming. If the time of the fire from ignition to flashover is short, then the weight of fuel consumed during that period is negligible and Eq. 11 may be used to calculate the fire duration. For the fire duration of a ventilation controlled fire , Eq. 11

becomes

$$\tau = 0.5 \frac{W}{R_v} = 0.5 \frac{wA}{R_v} \qquad (12)$$

A fire may be well-ventilated, as is the case when fuel is burned in the open, or in a compartment with a window that is large in relation to the fuel surface available, and then the rate of burning does not depend on window geometry, but increases in proportion to the surface area of the fuel. For this reason, fires of this type are often called fuel-surface controlled fires. The following relation may be used to approximate the burning rate of wood under these conditions:

$$R_f = 0.09 \ A_f \qquad (13)$$

where

R_f = fuel surface controlled burning rate, lb/min

A_f = fuel surface area, ft^2

The duration of a fuel-surface controlled fire may be calculated by substitution of R_f for R_v in Eq. 12.

The well-ventilated and ventilation controlled fires represent the two extreme conditions, and fires are possible in which both burning rate control mechanisms operate together. Typically, fires in compartments begin small in size and the fuel-surface control mechanism predominates initially. As the fire increases in size, the fuel surface may continue to

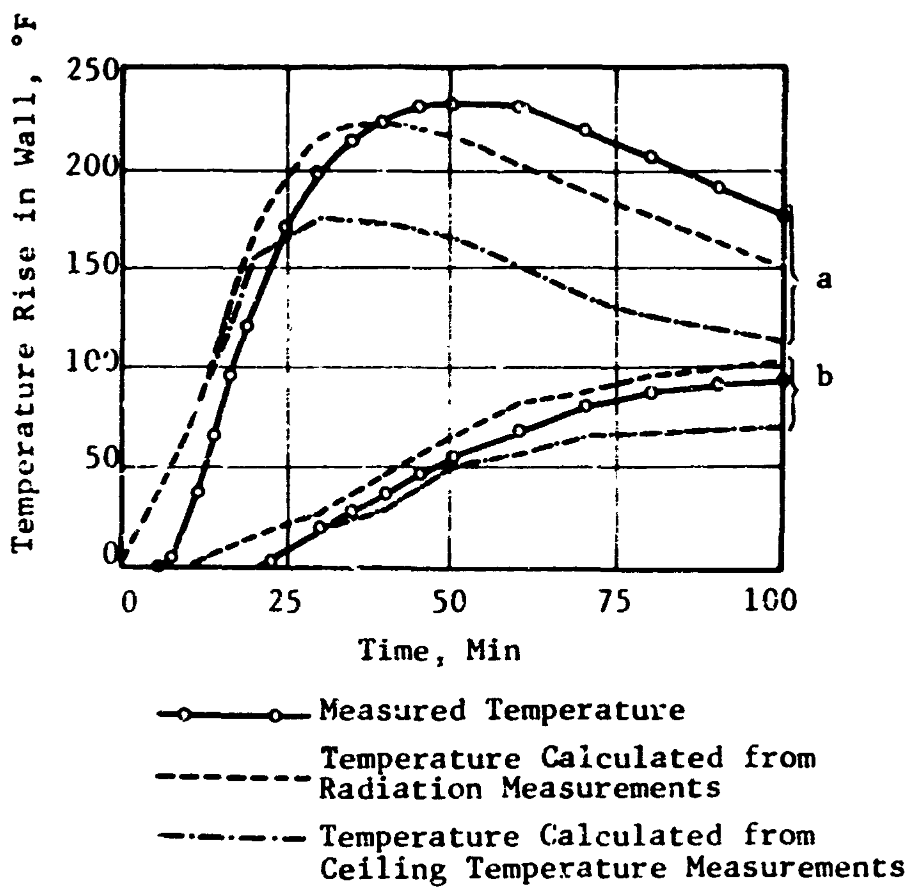
control burning rate exclusively, or some degree of ventilation control may eventually occur. While the time-temperature curves from various compartment fires may differ in shape because of fuel surface and ventilation conditions, they all exhibit the three major time periods previously described, i.e., ignition to flashover, maximum flaming, and decay to burnout.

Behavior of fire within a building is similar to the compartment fires described above, although compartments in buildings will vary in size, fire load, ventilation, and arrangement of fuel. Also, communicating compartments of a building may become involved by fire spread through unprotected openings. The duration of a compartment or building fire corresponds to the time period from A to B in Fig. 3, and to the violent burning time indicated in Fig. 4. The fire duration is given by a relation of the form of Eq. 12, with substitution of the proper burning rate, R_v, or R_f, depending upon the predominant control mechanism. It is general fire protection practice to assume that if the amount of fuel per unit floor area (fire load) is doubled, the fire duration and hence the fire resistance required for building components are also doubled. This will be true only when burning rate is independent of fuel loading (surface), as in a completely ventilation controlled fire. Except in very lightly loaded buildings, fires in fully-involved compartments will be predominantly ventilation controlled, and are of greatest interest.

Generally heat transfer to shelter components from fire within the shelter building is by thermal radiation and convection, as indicated in Fig. 2(b). After flashover in an adjoining compartment, the shelter component would be immersed in flame. Fire Research (11) reported the results of experiments in which an 8-foot cubical masonry enclosure with an opening on one side was subjected to a fully developed fire. Measurements were made of the radiation from the opening, rate of burning of the fuel, flame temperature within the enclosure, and the temperatures at two depths within the brick walls. The temperatures within the brick were then compared both with values calculated from the measured flame temperature at the ceiling and with values calculated by assuming a mean surface temperature equal to the effective radiating temperature of the enclosure. The results are shown in Fig. 5, from which it can be seen that the radiation measurements provide a better measure of structural temperature than measured flame temperatures. Although additional tests would be needed to verify this conclusion, the results suggest that a radiation intensity versus time curve may be used to predict the temperature distribution within a building component exposed to fire.

2. Carbon Monoxide Concentration In Fire Gases

It was stated in Chapter III that the flow rate of carbon monoxide through barriers into shelters would be used as a measure for rating shelter components. For fires within the shelter building, typical carbon monoxide concentrations



a--2-1/4 in. (5.7cm) inside wall from inner face

b--4-1/2 in. (11.4cm) inside wall from inner face

FIG 5 TEMPERATURE RISE INSIDE WALL OF 8-ft (2.4m) CUBICAL COMPARTMENT

can be chosen to describe various fire conditions on the fire side of a barrier. The carbon monoxide concentration in the fire gases will depend on the fuel composition, on whether the fire is predominantly fuel-surface controlled, or ventilation controlled, and on other fire conditions. Carbon monoxide concentrations found in fire gases in various experimental fires within buildings and compartments are given in Table II. On the basis of these data, it is suggested that an average CO concentration of 2 percent, and a maximum of 5 percent, are reasonable estimates for fuel-surface controlled fires. The corresponding values for ventilation controlled fires are 10 and 20 percent.

3. <u>Pressure Within An Enclosure During A Fire</u>

For fire gases to flow into a shelter through cracks, porous materials, and other openings in barriers, a pressure difference must exist between the fire side and the shelter side. This difference may derive from one or more of the following sources:

1. Thermal expansion of gases in an enclosure.
2. The generation of gases as a result of combustion reactions.
3. The buoyancy of confined hot gases.
4. Wind effects.

The first two sources are strictly the result of fire within an enclosure; whereas, the last two items may exist with or without fire.

TABLE II

CARBON MONOXIDE CONCENTRATION IN FIRE GASES WITHIN BUILDINGS

Reference Numbers Shown Refer to Reference In Bibliography	Fuel Surface Controlled Fires		Ventilation Controlled Fires	
	CO Conc. Range %	Remarks	CO Conc. Range %	Remarks
<u>KINGMAN, et al. (12)</u>				
Test No. 1	0 - 1.4	Before Flashover in Combustible Lined Dwelling	1.4 - 19.8	After Flashover in Combustible Lined Dwelling
Test No. 2	0 - 1.1	Before Flashover in Non-Combustible Lined Dwelling	1.6 - 3.8	After Flashover in Non-Combustible Lined Dwelling
<u>BRUCE (13)</u>				
Test No. 4	0 - 0.3	Before Flashover in Combustible Lined Room-Full Draft	0.7 - 1.4	After Flashover in Combustible Lined Room-Full Draft
Test No. 5	0 - 2.6	Before Flashover in Combustible Lined Room-Reduced Draft	4.5 - 13.8	After Flashover in Combustible Lined Room-Reduced Draft
Test No. 6	0 - 0.9	Before Flashover in Non-Combustible Lined Room-Reduced Draft	0.4 - 4.9	After Flashover in Non-Combustible Lined Room-Reduced Draft
<u>KAWAGOE (14)</u>				
Small Model Room-Chapter 2	0 - 5	Well Ventilated Steel Enclosure		
Paskin Concrete Block Room-Chapter 4		Not Reliable	4 - 14	After Flashover - Sample at Top of Window
Nissa Prefabricated Concrete Room Chapter 5	0 - 2	Before Flashover - Sample Near Top of Window	2 - 8.5	After Flashover - Sample Near Top of Window
Sasaki Concrete Block 2-Story Structure-Chapter 7	0 - 1	Before Flashover - Sample Near Top of Second Story Window	1 - 9	After Flashover - Sample Near Top of Second Story Window
Matsui Concrete Block 2-Story Structure-Chapter 8	0 - 1	Before Flashover - Sample Near Top of First Story Window	7 - 16	After Flashover - Sample Near Top of First Story Window
Concrete Block 2-Story Structure Chapter 9	0 - 2.5	Well Ventilated Fire - Sample Near Top of Window		
Light-Weight Concrete Protected Steel 2-Story Structure Chapter 11	0.03 - 0.1	Well Ventilated Fire Sample at Center of First Story		
<u>WATERMAN, et al. (15)</u>				
Ellis Parkway Burn. Second & Third Stories	0 - 5	Well Ventilated Fire - After Flashover		
Ellis Parkway Burn. First Story and Basement	0 - 1	Well Ventilated Fire - Before Flashover		

Although gases in an enclosure will undergo large thermal expansion because of heating by fire, significant pressure buildup would not normally occur in building compartments because of leakage through openings in the enclosure. For instance, if the temperature rise of the gases in an enclosure follows the ASTM E-119 standard time-temperature curve, only about 20 square inches of opening would prevent pressure buildup in a 1000 cu. ft. compartment. Since fire in a tight enclosure will not grow because of lack of oxygen, it seems reasonable to assume that all significant fires will be sufficiently vented to prevent buildup of pressure by thermal expansion alone. Furthermore, it can be shown that generation of gases by fires involving ordinary materials would always result in less pressure buildup than that caused by thermal expansion. Accordingly, items 1 and 2 are omitted from further discussion.

When the gas temperature in one building space is different from that in another, a pressure difference between these two spaces exists as a result of the difference in gas density. For the situation wherein there is no motion of the gases in the heated space,

$$\Delta P_b = 0.192 \rho_a h (T_b - T_a)/T_b \qquad (14)$$

where ΔP_b = theoretical pressure difference across an enclosure due to buoyancy of hot gases, inches-of-water column.

ρ_a = weight density of cold gas, lb/ft.^{3}

T_c = average temperature of cold gas, °R

T_h = average temperature of hot gas, °R

h = height of the hot gas column above the neutral plane, ft.

The neutral plane is that level at which there is no difference in pressure between the heated vertical shaft and its surroundings, due to buoyancy forces alone. A typical situation in which a pressure difference resulting from buoyancy forces may occur is shown in Fig. 6. In Fig. 6 the neutral plane is located at the bottom of the hot gas column. If there is flow of hot gases up the column, then fluid dynamic considerations must be applied to determine static pressure distribution in the column. An extremely tight shaft without upward gas flow will permit full pressure development, based upon the temperature attained, but the temperature increase within the shaft will be retarded. Ventilated shafts, on the other hand, will permit the temperature to rise quickly, but the static pressure rise will be reduced by the flow.

Based upon an air density of 0.075 lb/ft.^{3}, the velocity head equivalent of a given wind speed is given by the following equation:

$$P_w = 4.84 \times 10^{-4} V_w^2 \qquad (15)$$

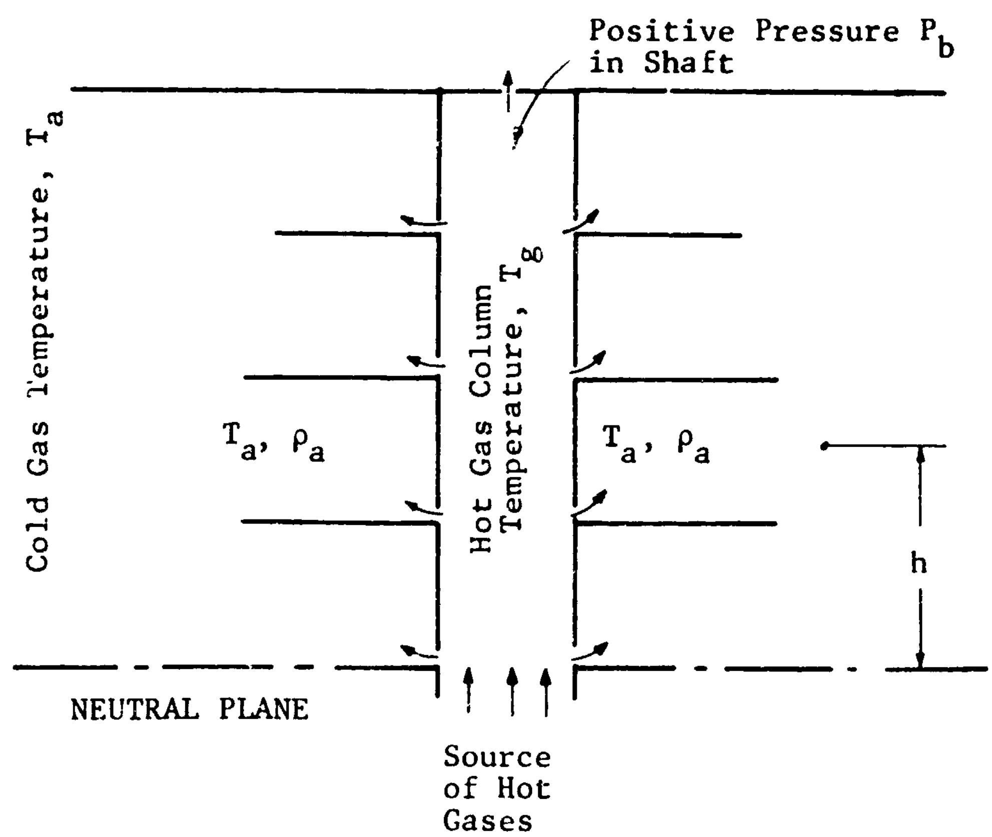


FIG. 6 A TYPICAL SITUATION IN WHICH BUOYANCY FORCES PRODUCE A PRESSURE DIFFERENCE

where

p_w = velocity head, inches-of-water

V_w = wind velocity, miles per hour

The static pressure over the exterior surfaces of buildings is approximately proportional to the velocity head of the undisturbed air stream. According to test data (16) on air infiltration through cracks around windows, the actual pressure difference ΔP_w across windward walls in a building may be approximated by the relation:

$$\Delta P_w = 0.64\ p_w \tag{16}$$

Thus, the theoretical absolute pressure (P_w) within a fire enclosure on the windward side of a building may be estimated by:

$$P_w = 3 \times 10^{-4}\ V_w^{\ 2} + P_a \tag{17}$$

In any given case, the greatest difficulty in assessing the effects of wind is to determine the actual wind velocity acting on the surface of a building. Shielding of one building by another results in significant reductions in effective wind velocities. Depending on direction, the static pressure due to wind acting on a building surface may be either above or below that in the undisturbed air stream. As a rule, pressures are positive on the windward side of a building and negative on the leeward side. Pressures on remaining sides may be positive or negative. In spite of all of these and other problems, for purposes of rating shelter components the ability of wind to cause pressure differences across barriers should be considered.

The actual pressure difference between the fire side and the shelter side of a barrier depends on the magnitude of all acting pressure forces. In order to provide a conservative estimate of the maximum positive pressure that may be developed outside a shelter in a burning building, it is suggested that the following relationship be used.

$$\Delta P_t = \Delta P_b + \Delta P_w = 0.192\,\rho_a\,h\,(T_g - T_a)/T_g + 3\mathrm{x}10^{-4} V_w^{\,2} \quad (18)$$

The term h will depend on the height of the shelter above ground, and the wind velocity will have to be based on weather bureau records of prevailing winds. It is reasonable to assign a temperature of 2060 °R to the fire gases.

C. EXPOSURE FROM FIRE IN INDIVIDUAL NEARBY BUILDINGS

1. Impinging Flame Exposure

This type of exposure exists when the shelter building is separated from the adjacent exposing building by a fire wall; also, when the exposed building is detached but close enough to permit flame to contact the shelter building. In both cases the exposed wall may be parapeted and without openings of any kind; this is to be desired. Where communicating openings between adjacent buildings are present, these are provided with standard fire-door protection in the fire wall; without standard fire-door protection the two buildings would no longer be considered as separate buildings in regard to fire protection. Where the exposed shelter building wall

has window openings and these are protected by wired-glass in metal frames, fire shutters, or are filled with glass blocks, such forms of protection are treated as shelter components in the appropriate section and rated accordingly. The above exposures are almost identical with the previously described exposure from fire within the shelter building. For this reason, reference is made to Section B of this chapter for details of fire behavior, carbon monoxide concentration in fire gases and pressure within an enclosure during a fire.

The ideal fire wall construction would allow burnout and collapse of the exposing building without destruction of the fire wall. To satisfy such a fire wall specification demands a stability against collapse or overturning far in excess of that offered by types of construction which perform well in fire tests alone. How well the behavior of a real fire wall would correspond to the ideal must be evaluated at the building site. Any opening in a fire wall constitutes a weakness, regardless of protection. However, standard fire-door protection has proven effective in many instances, especially when the doors are maintained normally in the closed position, and in good repair.

2. Distant Flame Exposure

In this case, the burning individual building is sufficiently distant that flame or hot fire gases do not contact the exposed shelter or shelter building, although

relatively cool fire gases driven by wind may contact the shelter. As previously defined, heat transfer from this exposure is due only to thermal radiation impinging upon the exposed structure. If in the shelter building some kind of barrier exists separating shelter and non-shelter areas, then the exposure may produce two kinds of effects:

1. The exposure may cause heating and ignition in non-shelter areas of the exposed building.
2. Thermal radiation impinging directly upon shelter components, may cause heating and ignition within the shelter.

Since this report pertains only to the rating of shelter components, the first of these two effects is beyond the scope of this work. Thus, in describing distant flame exposure, this discussion is confined to the thermal radiation emanating from a fire in a burning building, and its effect on shelter components.

Although knowledge is incomplete regarding those factors necessary to calculate thermal energy transmitted to shelter components by radiation from adjacent burning buildings, enough data are available for making reasonable estimates of upper bounds. It is required for this purpose to estimate the effective temperature and radiating area of flames in view of the component.

Such items as masonry wall panels, individual rein-

forced concrete columns and beams, exterior fire doors glass block wall panels, as well as wired-glass in metal frame window assemblies, may be isolated for individual consideration as receivers of thermal radiation.

Radiation will emanate from the burning building at all windows of compartments in which flashover has occurred, from flame above those windows, and, after roof penetration, from flame rising above the roof of the building. The radiating area of flames depends upon the extent of the fire spread within the building, whether or not the fire significantly penetrates the roof, as well as the fire conditions which determine the amount of flame projecting above windows.

The extent of fire spread expected within the building depends upon the type of construction. Buildings of fire resistive construction, with vertical openings completely protected, tend to burn one story at a time, and the fire may be confined to the floor of origin. If simultaneous ignition occurs on more than one story, then those stories so ignited can be expected to radiate at the same time. Buildings of fire resistive construction, with vertical openings unprotected, can be expected to become totally involved by fire and to radiate from all exterior wall openings. Buildings constructed with masonry walls and wood floors and roof, regardless of vertical opening protection, can be

expected eventually to become completely involved by fire, radiating from all wall openings, as well as from flames projecting above the roof. Buildings of wood construction also will become completely involved by fire internally and will radiate from all wall openings, as well as from flames above the roof. Exterior combustible walls will collapse before burning externally, unless heated by thermal radiation from another burning structure, or from another part of the same structure.

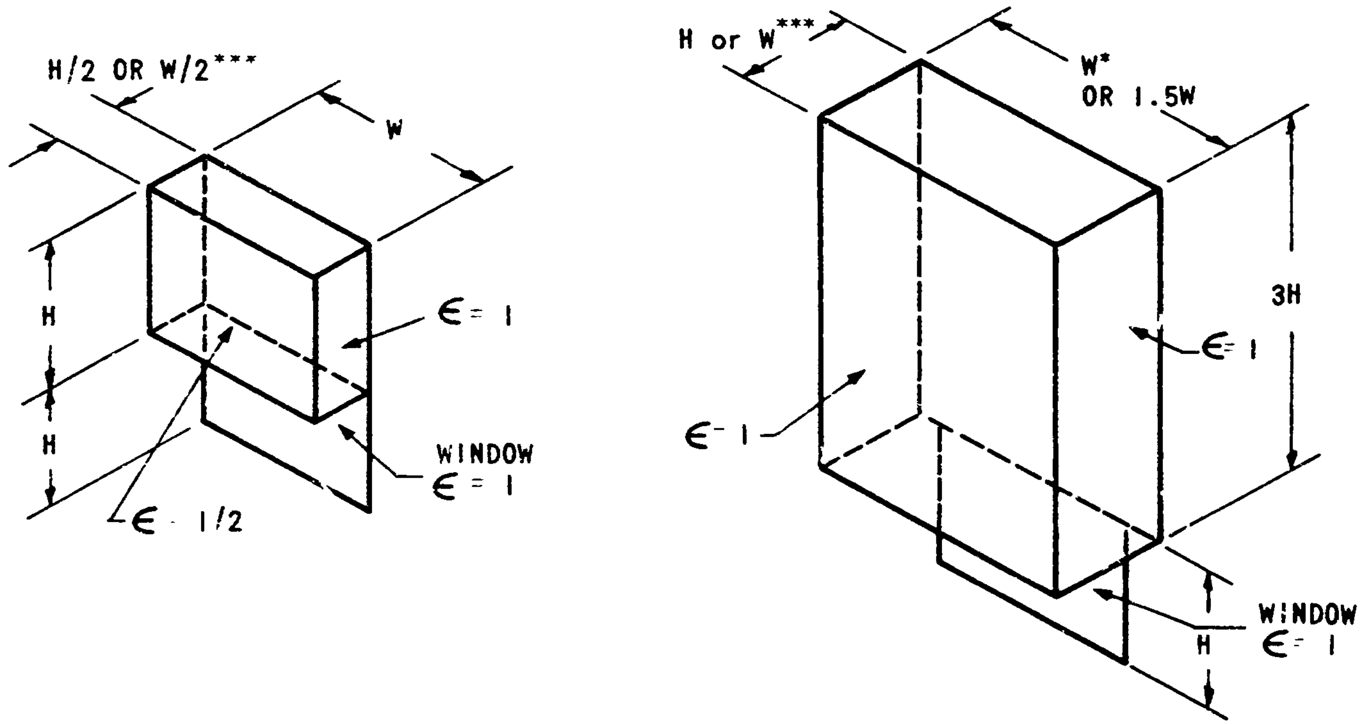
Salzberg et al. (1) have suggested a model for the evaluation of the area of the flame above the roof of a burning building after roof collapse. For fire resistive construction, the flame height is equal to one-half the story height; the flame width corresponds to the dimension of the building. For masonry wall and wood construction, or buildings of all wood construction, flame height above the roof is equal to one-half the building height; the flame width corresponds to the dimension of the building.

Waterman et al. (15) have described experimentally-determined models of flame radiation from windows during peak fire conditions within an enclosure. As shown in Fig. 7, these models enable calculation of the effective radiating area and of the intensity of thermal radiation emitted from window openings and from flames above windows. For the case in which a building burns one story at a time, Fig. 7 (a)

* W - WINDOWS ON ADJACENT WALLS
1.5W - WINDOWS VERTICALLY ALIGNED

** NO FLAME EXITS FROM FIRST STORY WINDOWS AT THIS TIME AND WINDOW OPENING CAN BE ASSUMED AT 1600°F ($\epsilon = 1$)

*** WHICHEVER SMALLER



(a) SINGLE ROOM (T=1500°F)

(b) SECOND STORY** AFTER CEILING COLLAPSE (T 1600°F)

FIG. 7 RADIATION MODELS FOR WINDOWS, FLAME ABOVE WINDOW, AND RADIATION TO THE SIDE

indicates a flame area above the window equal to the window area, and a thickness of one-half of the minimum window dimension. The window and flame both radiate at 1500°F, and the approximate emissivities (ϵ) are 1 and 1/2, respectively. Fig. 7 (b) describes conditions at the second story where the fire is burning simultaneously on two stories, and the ceiling between them has been penetrated sufficiently to allow essentially unrestricted flow between the two levels. In this case, the window at the lower level radiates at 1500°F, ϵ=1, with no flame above it. The area of flame above the second story window is equivalent to 4.5 window areas and has a thickness equivalent to the minimum window dimension. Also, the second story window and flame above it both radiate at 1600°F, and ϵ=1. The models of flame radiation from windows described in Fig. 7 are recommended for use with compartments having either combustible or noncombustible linings.

For estimating maximum flame radiation, one may use these flame models by assuming all adjacent buildings to be fully involved by fire and determining flame characteristics according to the type of construction. For fire-resistive construction, fires on all floors would be assigned the characteristics of one-story fires, and flames above the roof would be determined as though the roof had collapsed. For other kinds of construction, complete involvement by

fire will usually mean that flames are not emitted simultaneously by all window openings. However, it is suggested here that window radiation be estimated in these cases by considering 1.) the flames from one half of the windows to correspond to single story fires, 2.) the flames from one half of the windows to correspond to the second story of a two story fire, and 3.) the roof to be penetrated. Roof flames should be assigned a temperature of 1600°F and an emittance of one in all cases.

It remains to assign durations to the fire causing distant flame exposure. For this purpose, estimates by Chandler et al. (10) of burning times of individual buildings are useful. These are shown in Table III. According to the definitions given previously of violent and residual burning times, most of the thermal radiation would be emitted during the violent burning time. Use of this duration with the calculated peak radiation level should, therefore, provide a good estimate of the maximum total heat input to the shelter components. Part F of this section shows how allowance should be made for the residual burning time.

D. EXPOSURE FROM MASS FIRE

1. Fire Storm and Conflagration

There is a great lack of knowledge of the quantitative aspects of mass fire. However, it is believed that the general information available does include sufficient detail

TABLE III

BURNING TIME OF URBAN FUELS

Construction Type	Violent Burning Time Min.	Violent Burning Total Energy Release (%)	Residual Burning Time Min.	Residual Burning Total Energy Release (%)	Active Burning Time Min.
Light Residential	10	80	12	20	22
Heavy Residential	13		20	30	33
Commercial	25	60	60	40	85
City Center and Massive Manufacturing	55	30	120	70	175

to permit a description for purposes of rating shelter components.

The mass fire is conceived to be a large area fire in which flames from each burning structure coalesce into a single convection column. A mass fire may take one of the following forms:

1) A mass fire may exert control over the surrounding atmosphere, resulting in a stationary fire with air indraft from all directions, and is referred to as a fire storm.

2) A mass fire moving along a front under the influence of wind is referred to as a conflagration.

As a result of fire attacks on German cities during World War II, fire storms are said to have occurred at least in Hamburg and Dresden. According to Bond (17), "It was estimated that in Hamburg, within 20 minutes, two out of every three buildings were on fire within a 4.5 square-mile area.-------- As the many fires broke through the roofs of buildings, there rose a column of heated air more than 2 1/2 miles high and 1 1/2 miles in diameter, as measured by aircraft flying over Hamburg. This column was turbulent and was fed at its base by inrushing cooler ground-surface air. One and one-half miles from the fire this draft increased the wind velocity from 11 to 33 miles per hour." The mass fire extended over an area of nearly 17 square miles, with

an area of concentration of 4.5 square miles. While it is impossible to give accurate measurements of the actual peak wind velocities, it is believed that the local surface winds exceeded 75 m.p.h. According to the Hamburg Fire Department, hurricane velocities occurred in narrow streets, and the temperatures exceeded 1400°F in these locations. It has been stated (10) that the Hamburg fire storm had run its course in about three hours.

A fire storm developed also in Hiroshima, Japan, as a result of an atomic bomb. It is reported (18) that the fire storm was established about 20 minutes after detonation of the bomb; and that wind blew toward the bombed area of the city from all directions, reaching a maximum velocity of 30 to 40 miles per hour about 2 to 3 hours after the explosion, decreasing to light or moderate and variable in direction about six hours after.

One of the more notable examples of a conflagration type of mass fire occurred in Tokyo on March 9, 1945. According to Sanborn (19), "For this attack, eight square miles of the most highly combustible portion of the city had been chosen. An extended fire swept over 16 square miles in six hours. ---- The fire had spread largely in the direction of the natural wind".

Laiming (20) reported on the Tokyo conflagration of 1923, in which 17 square miles were destroyed in less than a

day. Wind at less than 20 miles per hour corresponds to fire travel of about 200 feet per hour (about 0.04 m.p.h.); wind over 20 miles per hour caused fire travel as high as 1500 feet per hour (about 0.3 m.p.h.).

Chandler et al. (10) have reported on 254 case histories of urban area fires, 195 of which were rejected for various reasons. However, data were obtained on 73 linear rates of spread on 23 different fires. Of these 73 linear rates of spread, 36 were recorded as ordinary ground spread, and 24 as spread by spotting (fire brands). The average ground spread rate was found to be about 0.1 mile per hour and the average rate of spread by the firebrand mode was about 1.0 mile per hour.

The duration of a mass fire is not known at the present time. Until more reliable information becomes available, the mass fire, either fire storm or conflagration, can be estimated to be of no longer duration than that fire which would occur if the structures in the area under study burned independently under no significant wind (22). Burning-rate reductions from oxygen deficiencies in mass fires probably tend to be offset by increases due to wind velocities, either prevailing or fire-generated.

Burning times of individual buildings estimated by Chandler et al. (10), have already been given in Table III. These values were determined by examining the records of

experimental test fires in actual buildings where time histories of radiation or temperature had been made at locations adjacent to the fire. The terms violent burning time, and residual burning time are defined in Section B of Chapter IV. Active Burning Times given in Table III can be considered to represent an approximate mass fire duration, but not the total fire duration. The period before the mass fire development, although probably less than one hour, may vary greatly with ignition density, together with building size, density, use (fuel loading), and internal layout.

In their analysis of the convection column above a fire storm, Nielsen et al. (21) considered a burning area with a radius of 5,000 feet, an area corresponding roughly to that involved in the fire storm which took place in Hamburg, Germany. They found that, all of the gaseous fuel supplied at the base of the convection column is consumed below an altitude of about 800 feet above the ground, and the peak temperature (3000°F) also occurs at this altitude. At an altitude of 1700 feet, the temperature in the column predicted by this model falls below 1000°F, the minimum temperature at which the column can emit appreciable visible radiation.

Fujita (22) reported that during fire experiments in wood buildings, Prof. M. Hamada found maximum temperatures during the peak time of fire in the range 2100 - 2500°F.

Measurements made by the National Bureau of Standards on fire tests of two and five-story brick and wood-joisted buildings showed that temperatures as high as 2000°F were reached in 20 minutes, and 2200 to 2400°F in 40 minutes (23) Beeson (24) states that the temperatures reached in mass fires probably will not exceed 1535 C (2795°F). The evidence suggests that the maximum flame temperature within a mass fire would be less than 3000°F, and that an average temperature of 2000°F would be a reasonable estimate for the purpose of shelter component rating.

There is nothing that presently indicates the range of carbon monoxide concentrations in the convection column during the active burning stages of a mass fire. According to Bond (17), carbon monoxide poisoning was a major cause of death after aerial bombing. "In Hamburg, 70 per cent of all casualties, apart from those resulting from mechanical causes or burns, were caused by carbon monoxide", Bond reported. However, this information does not lead to any particular conclusion about the carbon monoxide concentration in the convection column. Wilson (25) concluded that, "Extreme carbon monoxide concentrations are to be expected in and around large fires burning out of doors." In Wilson's experiments, carbon monoxide concentrations exceeded 2.7 per cent; instrument limitations prevented recording higher values. Nielsen et al. (21) give data from Schuster (26)

quoted by Akita (27) regarding changes in decomposition products with increase in the temperature at which wood is decomposed. For the temperature range 300 C (572°F) to 500 C (932°F), an approximately constant 30 per cent volume concentration of carbon monoxide is reported for wood distillation gases. This value can be considered as an upper limit of concentration of carbon monoxide in gases from mass fires. It is to be expected that the carbon monoxide concentration would be altered by dilution with air and chemical reaction. Until further data are available to provide a more reliable value, it is suggested that 20 per cent carbon monoxide concentration be used for rating shelter components exposed to mass fires

2. Exposure To Mass Fire

Clearly, there is a great deal of uncertainty concerning the duration and the actual environment within either a fire storm or conflagration. However, immersion of a shelter in either variety of mass fire will result in a very severe exposure, which is probably tolerable only for the blast shelter (as defined here). For rating purposes, it is recommended that, until further information is forthcoming, the following characteristics be assigned to the mass-fire environment:

Duration	Table III, Column 6
Temperature	2000 °F
CO concentration	20 per cent

Figure 8 is suggested as an interim guide for evaluating the intensity of distant flame exposures from mass fires on shelters. It is based on an approximated conflagration flame model 100 ft high of infinite width. This represents a conflagration separated from the shelter by a fire break which prevents envelopment. Estimates of the exposure due to a fire storm based on Nielsen's (21) model are of a lesser magnitude since location of the shelter beyond the fire perimeter automatically places it a great distance from the main column. Since it is expected that any area capable of supporting a fire storm can also support a conflagration, the conflagration estimate is given.

3. Debris Fire

In this report, debris is defined as the remains of an urban area resulting from a target response to a nuclear explosion. The proportion by weight, volume and surface area of combustible and non-combustible materials in a debris pile is related to these same proportions of materials as they existed in the structures and contents involved.

For example, consider a 25' x 67' x 40' high, three-story apartment building, with brick walls and wood joist floors and roof, and walls and partitions finished with plaster on wood lath (15). Table IV gives the proportions by weight, volume and surface area of the materials

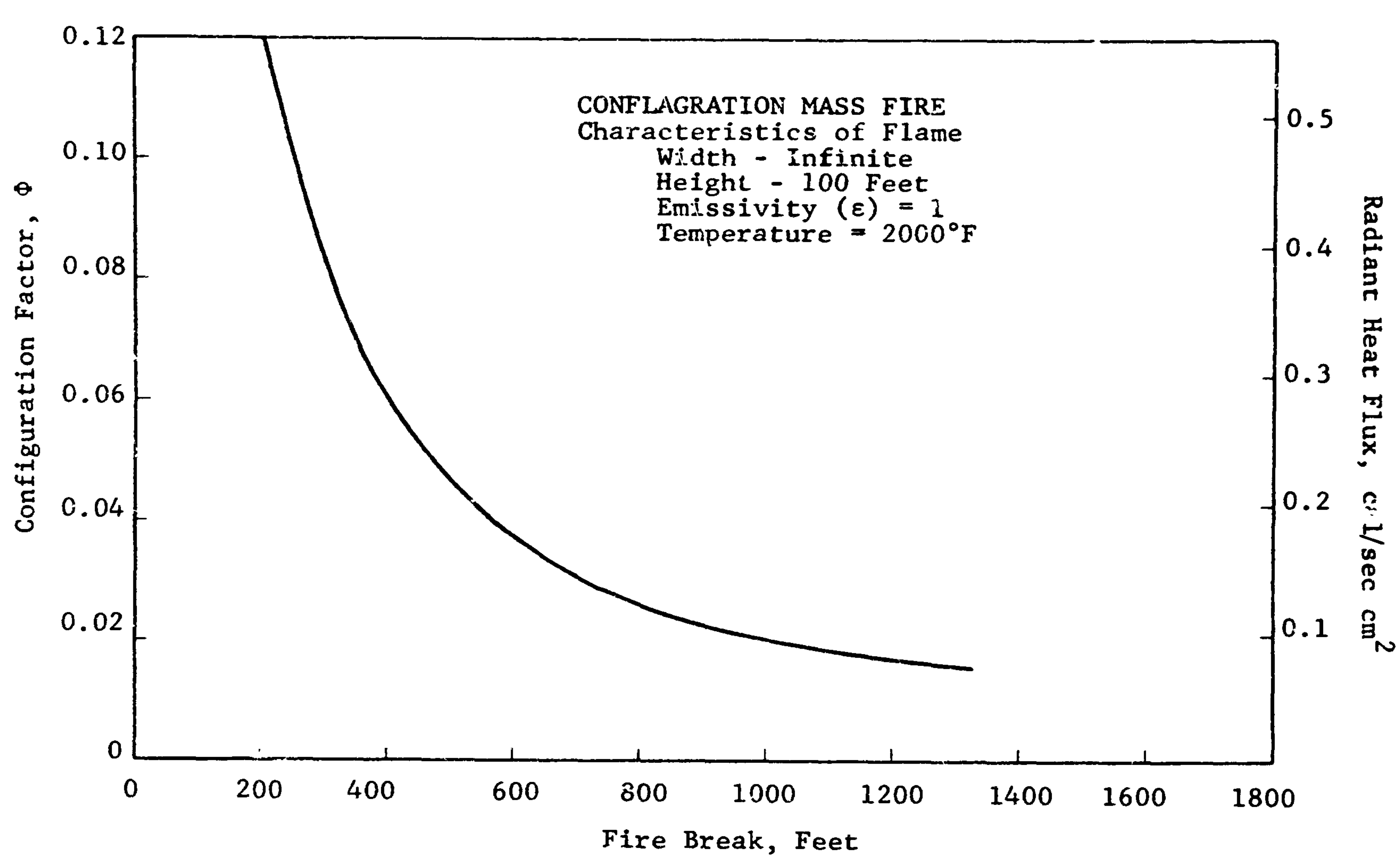


FIG. 8 INTERIM GUIDE FOR MASS FIRE - DISTANT FLAME EXPOSURES

TABLE IV

MATERIALS IN A THREE-STORY BRICK-MASONRY APARTMENT BUILDING

LOCATION	MATERIALS	WEIGHT[1]		VOLUME[1]		SURFACE AREA	
		lbs.	%	cu. ft.	%	sq. ft.	%
STRUCTURE	non-combustible	851,100	91	8,914	77	56,480	51
	combustible	73,680	8	2,456	21	47,843	44[3]
CONTENTS[2]	combustible	8,040	1	268	2	5,112	5
TOTALS		932,820	100	1',638	100	109,435	100

(1) Specific weight of brick masonry wall - 100 lb/ft^3

Specific weight of plaster - 45 lb/ft^3

Specific weight of wood and cellulose - 30 lb/ft^3

(2) Non-combustible contents negligible

(3) Of the 44%, 22% was wood lath, 13% was 2" x 10", 2" x 8" and 2" x 4" lumber, and 9% was flooring and roofing.

in the structure and the contents of this building. The surface area of the brick masonry was calculated on the assumption that fragmentation produced pieces 12" x 12" x 16" (1.3 cu. ft.). The total weight of combustibles in the building averaged 68 lbs/sq ft of building ground floor area, and the non-combustibles in the building averaged 710 lbs/sq ft. Although not necessarily true for other buildings, the non-combustible contents in this experimental building were found to be negligible. It is expected that the values in Table IV would be quite different if calculated for other occupancies and construction types. The surface area and distribution of debris are related to the extent of fragmentation of the structure and its contents; this in turn, is related to the location of the building with respect to ground zero. While the results may not be exact, the method described for calculating the values given in Table IV may be used as a first order approach to determine the constituents of a debris pile.

The blast effects of a nuclear explosion on typical structures is given in "The Effects of Nuclear Weapons" (28) as a function of weapon size, height of burst and distance from ground zero. According to this source, the example building (wall-bearing, masonry building, apartment-house type) would be severely damaged at peak overpressures of 5 to 6 psi, and moderately damaged at 3 to 4 psi over-

pressures. A 10 megaton weapon would produce severe and moderate damage at distances of 8.7 and 10 miles from ground zero, respectively. Observations of the actual damage to buildings of various types exposed to air blast from a nuclear explosion are further discussed in Chapter V of reference (28). Fig. 5.30 of this reference shows the remains of an unreinforced brick house, with wood floors and roof, after exposure to 5 psi overpressure; the exterior walls were exploded outward, the roof was blown off, leaving the interior wood floors and partitions severely damaged, but located on the original building site. Being predominantly wood and open to the atmosphere the debris would produce a relatively quick, hot fire.

The above discussion indicates that the type of debris resulting from a nuclear explosion will depend on the following factors:

1. Building construction types and occupancies
2. Location in target area with respect to ground zero
3. Size and height of weapon burst

For a given size of weapon and height of burst, the extent of fragmentation and displacement of buildings and contents decreases with increased distance from ground zero. According to Havers et al (29), most conventionally-designed buildings will be destroyed within the radius from ground

zero to 10 psi overpressure. A first approximation of debris depth has been made (30) by assuming that all of the buildings are fragmented and are deposited uniformly in the neighborhood of their original location. Selected findings of this study are listed in Table V, based upon a 50 per cent volume of voids in the rubble. The fragmentation of structures by the blast shock front will actually give a horizontal component of velocity, and the smaller fragments will tend to be hurled farther than the larger ones. Definition of effects producing nonuniform debris depths must await further studies.

The fire behavior of a debris pile varies with the kind of materials, the proportion by weight, volume and surface area of the individual combustible and non-combustible materials, as well as the weight per unit volume of the debris pile. After ignition, the rate of spread of fire and the burning rate of a debris pile will depend on the thickness of the pile, the flow rate of air to the fuel by means of wind effects, natural convection and diffusion, as well as the exposed fuel surface area. The temperature and flow rate of the fire gases and the surface area of the solids determine the rate of heat transfer to the solids in a debris pile. The quantity of heat stored in a debris pile, and therefore the temperature rise, depends upon the weight of materials and the values of their specific heats. The weight of available fuel and the burning rate determines the fire duration of a burning debris pile. This

TABLE V

Uniformly Distributed Debris Depths In
Typical Urban Neighborhoods

Neighborhood Description	Depth Of Uniformly Distributed Rubble
Central business district, a region of tall buildings with few vacant areas	12.6 ft.
Secondary or neighborhood commercial district	3.8 ft.
Region of high-rise apartments	2.1 ft.
Modern suburban shopping center	1.3 ft.
Residential neighborhoods of various building heights and densities	1.7 ft.

brief description shows how the various parameters enter into debris pile behavior.

Very little information is available on the temperature and duration of debris fires. What information does exist pertains to the debris remaining from burned-out building fires, which bears little relationship to the debris from blast-destroyed structures. A few rubble probings reported by Broido (31) indicate that portions of the debris resulting from the burnout of a municipal building in El Cerrito, California, were above 1900 °F and generating local carbon monoxide concentration greater than 1 per cent almost 24 hours after ignition. However, sufficient data were not collected to indicate the general temperature or gas concentration levels over the entire area. Other data available are the result of a full-scale fire test (23) in 1928 of a five-story, masonry-walled structure carrying an average fire load of 15 lb/sq ft floor area. The brick-covered debris remained at a temperature near 1000 °F for two to three days. Higher temperatures would be expected in actively burning debris piles; temperature levels of 1500 to 2000 °F would be more realistic. The pilot ignition temperature of wood, about 500 °F, would be a reasonable minimum in this case

The debris problem is recognized by the National Fire Code (32) Committees as indicated by the restrictions placed on record containers. Table VI gives the fire exposure

rating for record vaults to be used in non-fire-resistive buildings.

TABLE VI

EQUIPMENT FOR USE IN A NON-FIRE-RESISTIVE BUILDING

Total weight of combustibles including contents and building members of all floors including roof, but not exterior walls, lbs. per sq. ft. of ground area	Record Vault Rating
Less than 25 lbs.	2-hr vault rating
25 - 50	2-hr vault rating
50 - 100	4-hr for basement or ground story
	2-hr above ground
100 - 150	6-hr for basement or ground story
	4-hr for first story of building with basement
	2-hr for upper stories
Over 150	6-hr for first story of building with basement
	4-hr for second story
	2-hr for upper stories

Non-fire-resistive buildings can be defined as constructions that cannot withstand burning-out of contents without collapse. Table VI shows that 2 to 4 hours of additional fire exposure rating are required by the standard for vaults located in areas subject to debris accumulation. This additional fire exposure is not the expected duration of

debris fire, however. It is intended to represent an estimate of the duration of exposure to the standard test fire which would produce the same effect on the vault as would the debris fire.

For example, the severity of exposure of a real debris fire with a duration of about 10 hours at an average temperature near 1000 °F would be about 10,000 degree-hours. Judged by an equivalent area under the Standard Time-Temperature Curve, this severity corresponds approximately to a 6-hour exposure in a standard fire test. Since the experimental data used to define the record vault ratings given in Table VI are not referenced, the exact detail of their basis is undefined It is likely that these ratings resulted from the data by Ingberg reported in the 1928 tests [illegible] previously (23). In this case, the shorter time period (10 hours as compared to 2 or 3 days duration) would be the result of expected fire fighting operations

Due to the limited data available, Chandler, et al. (10) estimated the total burning time of fires in urban areas by obtaining the opinions of experienced city fire department personnel in various parts of the United States. The consensus of these opinions is given in Table VII.

TABLE VII

TOTAL BURNING TIME OF URBAN FIRES

Fuel Type	Estimated Total Burning Time	Debris Fire Duration
Light Residential	36 hours	18 hours
Heavy Residential	72 hours	36 hours
Commercial	7 days	3-1/2 days
City center and massive manufacturing	2 months	1 month

For the purpose intended, Chandler et al. defined the total burning time as "the period during which a large urban fire might remain stationary yet be capable of resuming active burning if conditions changed for the worse". The Hamburg firestorm area is rated by Chandler as comparable to the last category given in Table VII. These burning times seem quite large particularly those of the last two categories. For the present purpose of estimating debris fire duration, these values are certainly an upper limit, since they represent the duration of "hot pockets" rather than the duration of general debris-area fire duration. Until further data become available, it is suggested that 50 per cent of the total times indicated by Chandler et al. be used as the debris fire duration. The suggested values of Debris Fire Duration are given in column 3 of Table VII.

Debris fires may expose blast shelters, causing heat

transmission through the walls and roof. Probably of greater significance is the exposure of the shelter fresh air intake to hot gases contaminated with carbon monoxide, as well as heating of the intake tube passing up through the debris pile. If the debris fire burns out in a comparatively short time (6 to 8 hours), the exposure may be no more serious than a fire in an adjacent building. However, if the debris fire has a long duration (a number of days) at moderate to high temperatures, then shelter occupants will be in danger, unless a self-contained life support system has been provided. Probably the most harmful debris fire visualized is one of long duration low rate of burning, with high carbon monoxide concentration in the fire gases.

To summarize, until further information becomes available it is recommended that the following characteristics be applied to debris fires:

1. Temperature levels within a burning debris pile will range between 500 and 2000 °F.
2. The carbon monoxide concentration in the fire gases above a debris fire may be as high as 20 per cent, as described under Section D, Exposure From Mass Fire.
3. The pressure driving fire gases into a shelter will approximate existing wind pressure acting on a shelter component. A wind of 25 mph will produce a pressure above atmospheric equivalent to a head of

0.2 inches of water, according to Eq. 17, Part B of Chapter IV.

4. Debris fire duration is estimated as 18 hours for light residential, 36 hours for heavy residential, 3-1/2 days for commercial and 1 month for city center and massive manufacturing area fuels, as described in column 3 of Table VII.

E. Interim Guidance Fire Exposure Data

Data pertaining to various fire exposures described in this chapter are summarized in Table VIII. This information is to be used only for interim guidance until either validated by further research or modified to conform to experimental or other information.

With reference to Table VIII the four basic types of fire exposures are classified into eight exposures corresponding to previously-described modes of heat transfer. Eventually, the category of exposure from fire within the shelter building will be further subdivided to include degrees of ventilation of the fire, as well as conditions pertaining to a shelter somewhat removed from a fire.

As shown in Fig. 4, the violent burning time given in Table VIII for urban fires represents the period in which radiation intensity exceeds 50 per cent of the maximum value recorded. Existing information is inadequate to permit description of radiation-time, or temperature-time curves similar to Fig. 4 for various exposures. Instead, in Table

TABLE VIII

INTERIM GUIDANCE FOR URBAN FIRE EXPOSURE DATA

Urban Exposure Description		Exposure Classification	Temperature & Duration Of Exposures: Violent Burning Time Min.	Violent Burning Temp. (°F)	Residual Burning Time Min.	Residual Burning Temp. (°F)	Pressure Difference Driving Gas Through Components ΔP_t (in.-of-water)	Carbon Monoxide Concentration On Fire Side Of Component (%)
Exposure From Fire Within The Shelter Building		Impinging Flame Exposure	See Column 1, Table III	1600	See Column 3, Table III	See Fig. 9	0.5	2 - 10 See Note 2
Exposure From Fire In Individual Nearby Buildings		Impinging Flame Exposure	See Column 1, Table III	1600	See Column 3, Table III	See Fig. 9	0.5	2 - 10 See Note 1
		Distant Flame Exposure	See Column 1, Table III	1600	See Column 3, Table III	See Fig. 9	0.2	2 - 10 See Note 1
Exposure From Mass Fire	Fire Storm	Impinging Flame Exposure	See Column 1, Table III	2000	See Column 3, Table III	See Fig. 9	3.0 See Note 2	20
		Distant Flame Exposure	See Column 1, Table III		See Column 3, Table III	See Fig. 9	0.5	20
	Conflagration	Impinging Flame Exposure	See Column 1, Table III	2000	See Column 3, Table III	See Fig. 9	3.0 See Note 2	20
		Distant Flame Exposure	See Column 1, Table III	2000	See Column 3, Table III	See Fig. 9	0.5	20
Exposure From Debris Fire		Debris Fire Exposure	See Table VII	2000	See Table VII	2000	0.2	20

Notes For Table VIII

INTERIM GUIDANCE FIRE EXPOSURE DATA

1. Regarding carbon monoxide concentration on fire side of component.

   a. Use 2% for fuel-surface controlled fires.

   b. Use 10% for ventilation controlled fires.

2. Regarding the 3 inches-of-water pressure difference for exposure from mass fire, this value should be used only during the violent burning time.

VIII, each exposure has been assigned a constant temperature value, as discussed previously. This constant temperature is intended to apply from the beginning of the exposure fire through the violent burning time period. Table VIII refers to Table III for values of violent burning times pertaining to various construction types, and to Table VII for debris fire duration.

Residual burning times given in Table VIII for urban fires represents the period after peak, when radiation is between 50 percent and 10 percent of the maximum value. Analysis of radiation-time curves presented by Fujita (22) indicates that, when the ratio I/I_{max} varies between the values 0.5 to 0.1, the radiation intensity from a high fire load single building fire decays according to the relation.

$$I/I_{max} = 0.5\, e^{-\tau/m} \qquad (18)$$

where τ = Residual burning time, minutes, such that $\tau = 0$ when $I/I_{max} = 0.5$

m = Time constant, minutes, different for each construction type

The curves in Fig. 9 were developed from Eq. 18 on the assumption that the decay period for other fires would follow the same function. Values of the time constant m, which pertain to the various construction types listed in Table III, are given in Fig. 9.

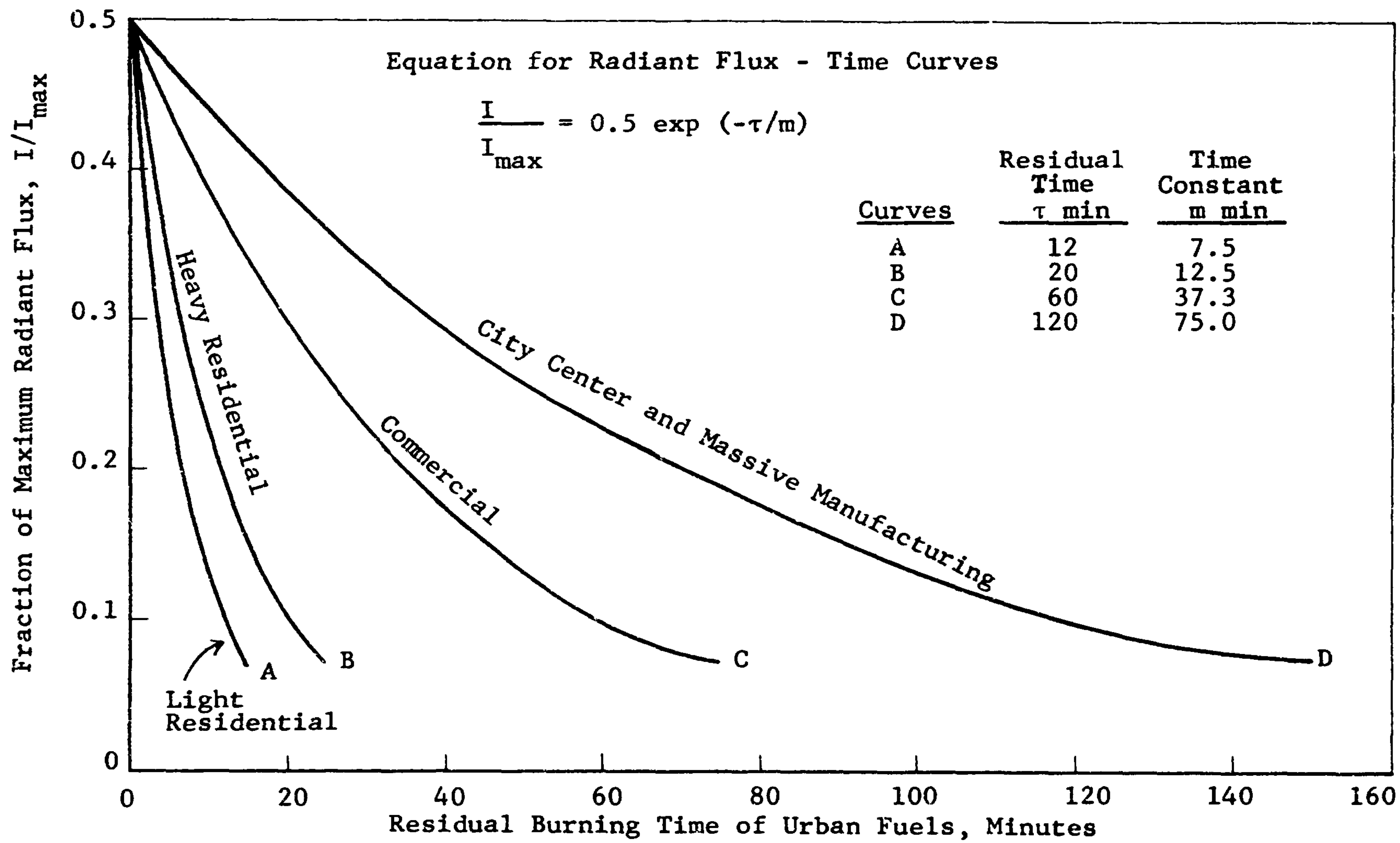


FIG. 9 RADIANT FLUX - TIME APPROXIMATION FOR RESIDUAL BURNING PERIOD

Since the radiant intensities I and I_{max} are given by the equations,

$$I = \epsilon_1 \sigma T^4 = \epsilon_1 \sigma (t + 460)^4 \qquad (19)$$

and $$I_{max} = \epsilon_2 \sigma \, T_{max}^{\;4} = \epsilon_2 \sigma (t_{max} + 460)^4 \qquad (20)$$

for $\epsilon_1 = \epsilon_2$, it follows that

$$\frac{I}{I_{max}} = \left(\frac{T}{T_{max}}\right)^4 = \left(\frac{t + 460}{t_{max} + 460}\right)^4 \qquad (21)$$

Then combination of Eq. 18 with Eq. 21 gives

$$\frac{t + 460}{t_{max} + 460} = 0.84 \, e^{-\tau/4m} \qquad (22)$$

The curves in Fig. 10 were developed from Eq. 22. Based upon the radiant flux-time approximation for the residual burning period, at any given time these curves represent the temperature of the source required to produce a given radiation intensity. These curves should not be used below a temperature of 500°F, since flame radiation becomes negligible below 900°F, and fuel temperature below 500°F is negligible for fire exposure considerations.

The pressure difference, ΔP_t, available to force gas through a component into a shelter, corresponds to effective pressures derived from fire phenomena and wind effects. Within

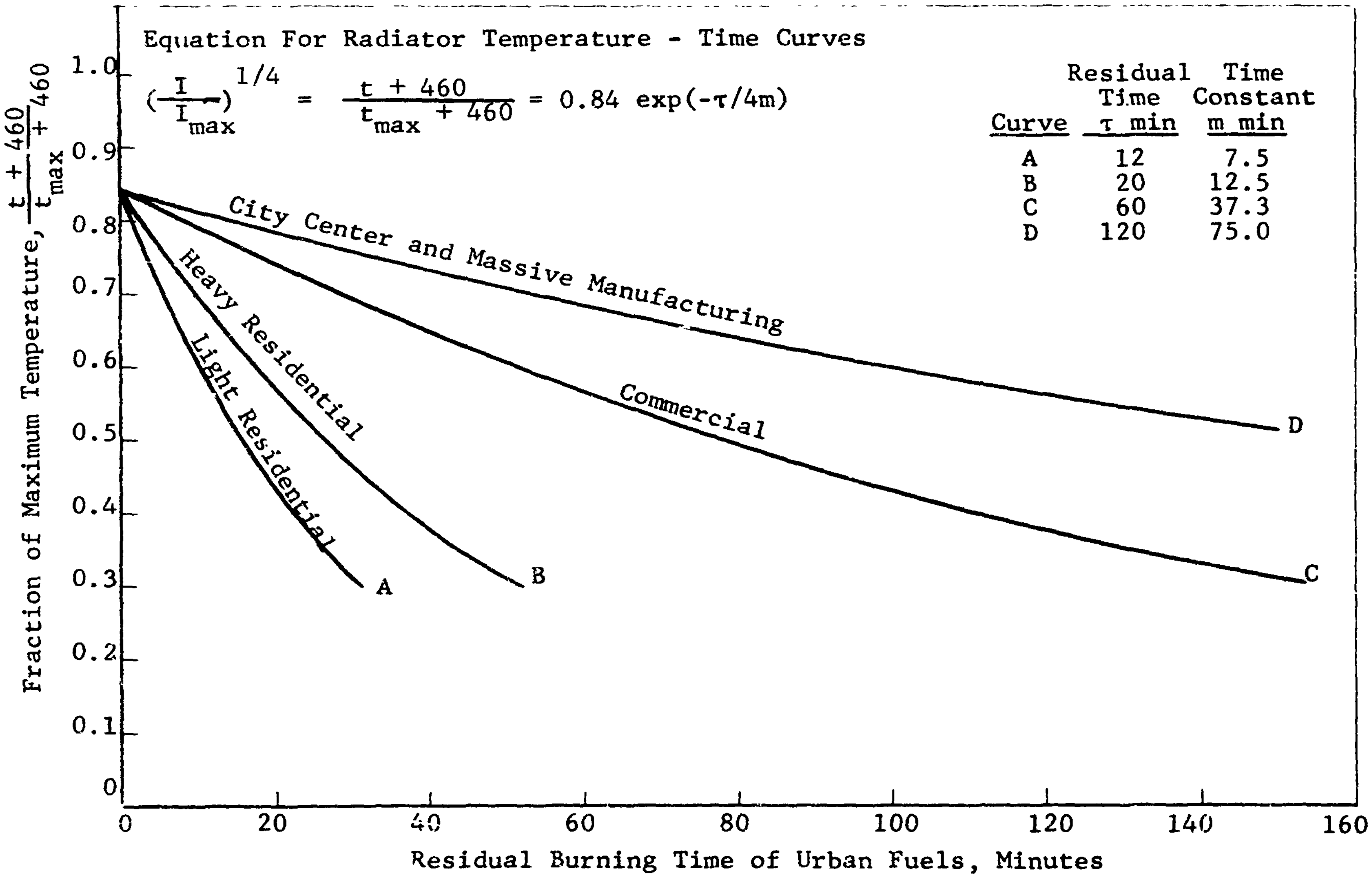


FIG. 10 TEMPERATURE - TIME APPROXIMATION FOR RESIDUAL BURNING PERIOD

the shelter building, 0.5 inches-of-water pressure represents the combined effects of fire and a 25 mph wind, estimated according to Eq. 18. The remainder of the ΔP_t values are primarily due to wind effects; 0.2 inches-of-water pressure represents the pressure difference due to a 25 mph wind, 0.5 inches-of-water pressure a 40 mph wind, and 3.0 inches-of-water pressure a 100 mph wind.

Fire side carbon monoxide concentrations are discussed in Chapter IV. A 2 per cent concentration should be used for fuel-surface controlled (well-ventilated) fires; 10 per cent for ventilation controlled fires. Considering that for gases distilled from wood, sometimes referred to as wood gas, carbon monoxide concentrations as high as 30 per cent have been measured, the 20 per cent concentration in Table VIII may be thought of as wood gas diluted with air.

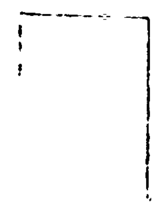
V. FIRE TEST RATING OF SHELTER COMPONENTS

A. Approach To The Test Method

To preserve the integrity of a shelter exposed to fire, it is essential that a number of performance requirements be met by each component of the shelter barrier singly or in combination with other components. The ability of the components to perform must also be assessed for a number of fire conditions, any one of which might occur in practice. The evaluation of performance may be either unique to the barrier (example: fire spread), or may only supply information which must be subsequently used to evaluate the true worth of the barrier in relation to the shelter size or the performance of other components (example: heat transmission or carbon monoxide infiltration). The numerous fire exposures and barrier performance requirements are summarized in Fig. 11.

Were one to develop a separate test to assess each requirement for each exposure, the result would be most unwieldy and require a prohibitive number of test facilities, as well as an unreasonable number of specimens. Fortunately, such an approach is not necessary. All exposures can be described as time-variable functions of temperature, pressure and carbon monoxide concentration. Similarly, performance can be classed as allowable temperature or quantity of gas flow, or absence of structural collapse. In all cases, it is the temperature rise resulting from exposure which causes changes

BARRIER



BLAST SHELTER EXPOSURES

1. Fire in Adjacent Buildings
2. Mass Fire
   a. Fire Storm
   b. Conflagration
3. Debris Fire

FALLOUT SHELTER EXPOSURES

1. Fire in Adjacent Buildings
2. Fire Within the Shelter Building
   a. Ventilation Controlled Fire
   b. Fuel Controlled Fire

BARRIER PERFORMANCE REQUIREMENTS

1. Resist Heat Transmission into Shelter
   a. Prevent Space Temperature Rise Unsafe for Occupants
   b. Prevent Toxic Gas Generation by Heating of a Barrier Surface Coating
2. Resist Infiltration of Fire Gases into Shelter
   a. Prevent Buildup of Unsafe Carbon Monoxide Concentration
3. Resist Fire Spread into Shelter
4. Resist Structural Collapse

FIG. 11 SHELTER COMPONENT FIRE TEST CONDITIONS

in the barrier itself. Thus, a single test which properly varies the surface temperature on the exposed side of the test specimen is sufficient to permit full evaluation of the barrier to the fire situation being simulated. Evaluation of the various performance requirements consists merely of monitoring sufficient parameters during and after the test exposure There is a further possibility (and a quite probable one) that each fire situation need not be simulated but that performance in certain fire situations can be inferred from a small number of standard exposures. Present practice in this area was discussed in Chapter II

The purpose of this chapter is to describe a usable system for evaluating shelter components, to define the degree to which present test methods or facilities are compatible with it to describe any necessary additions to the standard methods of test and to illustrate a potential form of presentation of results and their utilization

B. Utilization Of Present Test Methods

1. Present Procedures And Facilities

The use of full-scale room-size assemblies is characteristic of present fire testing procedures. Furnaces are provided which will expose, with flames of adequate depth, such assemblies mounted in realistic orientation. A means is provided for applying loads to bearing members Doors and windows are mounted into wall sections and tested in the same

manner as other vertical assemblies.

In these tests, observations and measurements of material behavior are made as loads are initially applied, throughout the fire exposure and following the exposure. Quantitative information includes: 1) the physical description of the assembly before testing, 2) the loading applied, 3) temperatures of the furnace and of the exposed and unexposed sides of the assembly, and 4) the deflection of the assembly. Qualitative observations of the surface characteristics of the sample are made which include: charring and color changes, cracking or spalling, indications of moisture release from concrete and plaster, and oxidation and erosion of steel members.

This approach is immediately compatible with shelter component testing. Both vertical and horizontal furnaces could be readily equipped with gas collection systems such as would be needed for the additional shelter functions described above. Such additions would not interfere with post-exposure overloads or hose stream applications. Circular furnaces presently used in column tests would appear to have little application in the testing of shelter fire barriers.

2. Restraint Of Test Assemblies

Several problems involving restraint of test specimens, which are encountered in present testing, will persist with shelter component testing. Inasmuch as room-size portions of

construction assemblies are being tested, the restraint on these assemblies in the furnace mounting should represent the forces opposing expansion in a real structure The difficulty lies not in the size of the test assembly, but in determining what the forces in a real structure are and how they can be synthesized.

Of the two simple alternatives considered in the development of fire test procedures, complete restraint was apparently preferred to none at all. The appearance of restrained building components after fire test was a decisive factor, since the conditions noted resembled the structural deterioration or collapse observed after actual fires. (33) Thus, the "Standard Methods of Fire Tests of Building Construction and Materials", ASTM E-119, makes specific requirements for restraint in testing building components. Bearing walls and partitions are loaded but not restrained at their vertical edges. In this way, these vertically oriented load bearing members, including columns, are allowed to move the load under forces of expansion. Non-bearing walls are restrained on all four edges; beams and floor members are rigidly contained in the horizontal directions. Apparently, complete restraint was felt to be conservative and readily reproducible. This is in accord with the general philosophy of repetitive testing as stated by R. W. Bletzacker (4). "In the broad sense, it is not important that the test simulate

some real condition but that the test be reasonable". However, some more recent tests (34) have indicated that situations are occurring in which a substantial portion of the test load has been transfered to the restraining frame, and the question has been raised as to whether the tests are either sufficiently conservative or reasonably realistic.

Experimental fires in one and two room structures of reinforced concrete and protected steel were reported by Kawagoe (35) and indicate the deformations which may be expected in structures with moderately restrained components. Inasmuch as every wall in these structures was an outside wall, the minimum structural interaction was observed in this series. In these room tests, deflections were measured in three directions, with the least expansion found in the vertical members. The horizontal deflection, until excessive, does not appear to be in itself structural failure. Further, a principal condition leading to failure in these rooms was a differential expansion of one material relative to another within the same assembly. Had the restraint been artificially increased, unequal elongation of the two materials in this assembly would have been restricted and this type of failure prevented.

The consequences of complete restraint have been demonstrated in experiments conducted by Selvaggio and Carlson (36) using twin-tee, prestressed concrete, flexural members.

Conclusions from this study include the following:

1. The thermal thrust on the test members from the fire exposure varied exponentially with the restriction of thermal expansion.
2. The shear type spalling, occurring in the members having highly restricted movement, will occur within 20 to 40 minutes from the start of the test if it takes place at all. After this time, the stresses are apparently relieved by plastic flow of concrete at the higher temperatures.
3. "A relatively large amount of longitudinal thermal expansion in restrained flexural members can be accommodated with very satisfactory structural performance in fire exposures". (Also observed in the Japanese experiments described above).
4. "The large thermal thrusts which developed in some of the tests indicate that full restraint in a building fire is not likely. The forces are greater than most abutting or restraining constructions found in buildings can accommodate without significant deformation."

It is thus clear that complete restraint in fire tests of structural components is very unrealistic and that it produces large thermal stresses which may either fracture the test specimen or cause substantial loss of the imposed load to the restraining frame. At the other extreme, it would be misleading to test unrestrained panels. Restraint less than that which would simulate the effects of panels joined perpendicularly at corners should not be considered. There-

fore, an intermediate restraint criterion is deemed necessary.

The following interim approach for the modification of existing restraining methods is recommended. First, the value of edge restraint should be limited to a fixed value, specifically, that of horizontal moment bracing for the least dimension of an average building (assumed here to be 80 feet). Requirements for resistance to wind load for buildings up to 300 feet high are generally between 20 and 30 psf but are higher in some areas. Earthquake loading requirements for seismic areas are generally a function of the vertically acting load. (37) (38) If the higher wind value is chosen to allow in part for earthquake load, a 30 psf load acting horizontally on a panel 12-1/2 feet high with a width of 80 feet, provides an average structural design resistance of 30,000 pounds. This would be applied to each 12 feet of edge of the assembly under test. Thus, deformations would be prevented only until the thermal thrust exceeded that force.

Secondly, the resisting influence of the unheated portions upon the floor or roof unit can be simulated to some degree by utilizing test assemblies extending 25 percent beyond the edge of the fire exposure boundaries before the primary restraint is applied.

The restraint criterion is described as applying to horizontal assemblies. In walls and partitions, the same maximum forces should resist the horizontal expansions. For

load bearing walls and partitions, the design load should resist vertical expansions as presently required. When non-bearing, such constructions should not have vertical movement restrained beyond the point that they would assume a vertical load appropriate to a bearing member.

Analysis and further refinement of restraint technique requires experimental verification. Such a program is discussed in Section VI. F.

C. Modification Of Existing Facilities

Two significant additions or modifications to existing test furnace assemblies will be required before they can be used in the rating of shelter components. The first of these concerns specimen restraint and was discussed in Section B. This modification, based on the results of the verification experiments, should be recommended for incorporation in peacetime rating tests, as well as in shelter rating tests, since present techniques do not adequately simulate reality in all cases.

The second addition to present test facilities is designed to permit evaluation of the direct flow of gases from the fire side to the shelter side of the component barrier under test. It consists of enclosing the unexposed side of the test specimen (attachment at the furnace frame) so that a small pressure difference can be maintained across the specimen throughout the test. By monitoring this pressure difference

and the quantity of gas pumped to maintain it, the leakage is determined. Since leakage rate is proportional to the square root of the pressure difference, the rate under any given pressure condition can then be calculated.

D. Publication And Utilization Of Test Results

As mentioned in Chapter II, present day fire rating procedures are predicated on an equivalence of fire exposure obtained by comparison of the product of temperature (above a base level) and time. With this basis, the relative merit of any given structural component can be expressed as a time of exposure to a standard fire. The validity of quite so simple a relationship to the wide variations of exposure situations for a shelter is doubtful. Thus, on the presumption that all fire exposures cannot be so simply correlated, it is suggested that the fire test data for shelter components be published for each exposure condition. In this manner, the user is relieved of the responsibility of proper interpretation from a single set of fire test results. This is particularly important, since each fire exposure corresponds to specific carbon monoxide concentration, pressure, and temperature history. It is also important to recognize that the length of a test performed on any given component is determined by the duration of the particular type of exposure for which the component is to be rated.

In considering this problem, the first concern should

be the condition of the shelter components undisturbed by fire exposure. Certain components, such as doors, windows, cracked walls and floors, may be exposed to the gases issuing from an active fire. Under these conditions, a pressure difference across the barrier which causes leakage will result in a buildup of carbon monoxide in the shelter. Whether or not such a flow rate can be tolerated depends upon the volume of the shelter and the facilities available to remove carbon monoxide from the shelter atmosphere.

For each type of fire exposure, the shelter designer should have at his disposal the following kinds of information regarding the shelter component of interest:

1. <u>Thermal flux transferred through the component versus time</u>

With this information the shelter designer can determine the temperature rise within the shelter space as a function of time. It is apparent that the permissible heat transmission of a shelter component depends upon the shelter volume, the area of the component exposed to the shelter space, and the capacity of the shelter space cooling equipment.

2. <u>Temperature-time curve measured on the unexposed surface of the component</u>

With this information the shelter designer can determine the exposure time required for the shelter side of the component to reach some predetermined unsafe temperature.

3. Flow rate of gas through component versus time

As the fire exposure runs its course, the gas flow rate can be expected to increase as the condition of the component deteriorates.

4. Equivalent flow rate of carbon monoxide through component versus time

From the gas flow rate through the component, the volume of the shelter, and the concentration of carbon monoxide in the fire gases, the buildup of carbon monoxide within the shelter can be predicted. Equation 9 (repeated below) may be used to evaluate the permissible time of exposure τ_c.

$$X_f \left\{ \tau_c + \frac{V}{Q} \left[\exp\left(-\tau_c\, Q/V\right) - 1 \right] \right\} = 4.5 \qquad (9)$$

5. Component collapse time

For the purpose of rating shelter components, it is desirable to continue the test of a component either until collapse occurs, or for the duration of an actual exposure. The full effect of an exposure on a component cannot be determined until it has run its course. Prior to this, however, other significant endpoints such as collapse of the component, may develop and should be noted. For any given component and type of exposure, the collapse time will probably be influenced by the applied loads, including loads associated with the kind of restraint applied to the test specimen.

It is apparent from the above remarks about shelter component test results and utilization, that the information cannot be reported as a single point value representing a minimum acceptable standard. The test results need to be presented in graphical or tabular form. There is no doubt that as a test proceeds certain data may exceed the practical range of values, such as for thermal flux density, temperature, or equivalent carbon monoxide flow rate. This does not mean that complete test data should not be collected; it means merely that the information reported should be confined to the practical range of values. In each case, of course, the practical range of values can be determined only after test experience is obtained.

VI. VERIFICATION EXPERIMENTS

Included within the scope of this project was the design of experiments to verify the applicability of the test procedures developed for shelter components. However, it was determined quite early in the study that, for the most part, the values assigned to the input parameters (temperature, pressure, CO concentration vs. time) of the various types of fire exposure were in need of evaluation. Thus, the majority of the experiments detailed below are designed for this purpose. Section E describes experiments concerning the prediction of the effects of each exposure condition by extrapolation of results from "standardized" exposures. Only Section F, the verification of sample restraint techniques, truly represents a verification of a test procedure.

The experiments reflect the general philosophy that experimentation under controlled laboratory conditions is most desirable. Under such conditions, systematic variation of parameters and repeat experiments are readily obtainable. Full-scale fires involving complete structures are suggested only to provide check points and to determine if any interaction of components exists which might be masked by studying component modules or segments in the laboratory.

A. Conditions of Exposure From Interior Fires

1. Background

To describe the exposure of shelter components by fire

within the shelter building, it is necessary to know whether the fire is ventilation-controlled, fuel-controlled, or some combination of the two. The influence of degree of ventilation on exposure temperature, fire duration, carbon monoxide concentration and gas pressure is also required. These fire exposure conditions are discussed in Section B of Chapter IV.

2. Scope

The scope of the work includes study of the behavior of enclosure fires involving various fuel loads, fuel distribution, and degrees of ventilation. The experiments should be designed to evaluate temperature, pressure, and carbon monoxide concentration after full involvement of combustibles within a compartment. The extremes of fire conditions and a few intermediate conditions should be examined to identify the fire conditions important to the rating of shelter components. These fire conditions should then be related to real occupancy construction types found adjacent to a shelter compartment.

3. Approach

Full-scale room fires conducted in an instrument test chamber, which simulates the room size typically found in residential and other structures are proposed. The room would be loaded either with real or simulated items and ignited in selected locations. Some experiments would be conducted under conditions where a well-ventilated fire is assured, while others would have varying degrees of ventilation. When

ventilation is very poor, the resulting fire conditions may tend toward relatively low temperature but high carbon monoxide concentrations. The important regions of exposure conditions need to be identified and interpreted.

B. Temperature and Pressure Within An Enclosure At a Distance From a Fire

1. Background

When the gas temperature in one building space is different from that in another, a pressure difference exists between these two spaces as a result of a difference in gas density. At some elevations, the space with the higher gas temperature will have a positive pressure with respect to its surrounding spaces. The force of buoyancy producing the positive pressure is equal to the weight of cold fluid displaced by the hot gas. Pressure within an enclosure during a fire is discussed in Part 3 of Section B, Chapter IV.

2. Scope

The objective of an experimental study of the temperature and pressure within an enclosure at a distance from a fire is to enable an evaluation of the flow of fire gases through a component into a shelter. Two geometrical arrangements need to be considered:

a. Fire generating hot gases flowing into the bottom of a vertical shaft, such as a stairwell or elevator shaft. A shelter space may adjoin the shaft at various levels.

b. Fire generating hot gases flowing into one end of a long corridor. A shelter space may adjoin the corridor at various locations along its length.

For these two kinds of situations, temperature, pressure and carbon monoxide concentration need to be determined for fires of various sizes.

2. Approach

Experiments using full-scale corridor and shaft facilities are proposed, the shaft to be at least four stories high; the corridor would be some convenient length. Various sizes of openings in the corridor, or in the shaft should be used to produce significant changes in flow in these spaces. Values of temperature, pressure and carbon monoxide concentration must be measured along the length of the corridor and along the height of the shaft. The important regions of exposure conditions need to be identified and interpreted.

C. Mass Fire Exposure Models

1. Background

For the purpose of rating shelter components, it is necessary to more clearly define a mass fire type of exposure than existing information permits. At the present time, the duration of a mass fire is not known. Until more reliable information becomes available, a mass fire, either fire storm or conflagration, can be estimated to be of no longer duration than the fire which would occur if the structures in the area

under study burned independently under no significant wind. Burning times of individual buildings were estimated by Chandler, et al. (10), and are given in Table III as approximate mass fire durations. It is also necessary to know the effective exposure temperature of a mass fire, as well as the rate of spread of a conflagration.

From the viewpoint of obtaining exact simulation of all of the conditions of a fire storm, the experimental data to supplement analytical studies should be obtained from a fire of as large a scale as possible. There are disadvantages to such large scale experiments, however, such as high cost and inaccuracy in experimental techniques.

2. Scope

The scope of the work should include the following:

a. An experimental program to provide information for the fire storm models. The experimental results would then be used either to validate the analytical models or to determine what modifications should be made to bring them into accord with the experimental results.

b. An analytical study of a large fire moving along a front under the influence of wind to develop a theoretical model of a conflagration type of mass fire. The analytical study may then be followed by an experimental program to provide information for the model.

3. Approach

To provide information for the fire storm models, much useful data could be obtained from experiments on a moderate scale in which precise measurement techniques could be used. The apparatus shown in Fig. 12 consists of a circular platform, 16 feet in diameter, with a source of hot air or combustible gas, 6 feet in diameter. The size of the fuel source is large enough to produce the same type of flow occurring in a fire storm with regard to flow direction and temperature, even though it is of a smaller scale. Since instruments are not available which can measure the velocity of a burning gas, initial experiments would be performed using heated air. Measurements of the velocity distribution would be made using hot wire anemomenters and of the temperature distribution using thermocouples. Since swirl flow can produce significant velocity effects, vortex motion would be produced in some of the experiments by using a ring of baffles, or a rotating screen, on the periphery of the platform. This experiment would be used to check the predictions of flow and temperature of the fire storm models at ground level and in the convection column.

Subsequent experiments would be performed using LP-gas. Measurements would be made of the gas composition within the convection column. Verification of the theoretical predictions of the oxygen concentration near the surface of the porous bed are

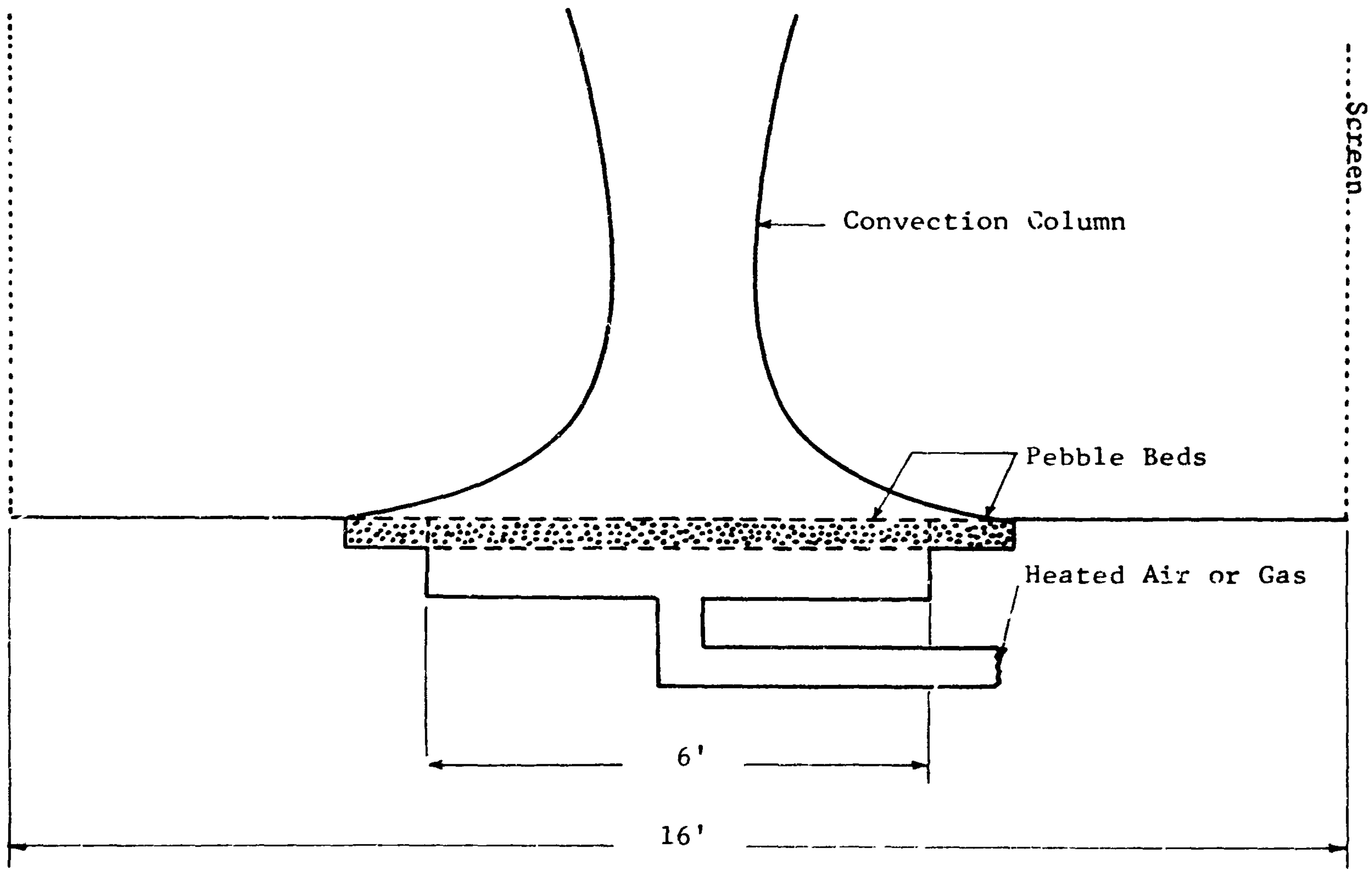


FIG. 12 SIDE VIEW OF APPARATUS FOR FIRE STORM VERIFICATION

especially important in regard to shelter ventilation possibilities.

Although it has long been known that one of the factors determining the behavior of flames was the effect of wind, it has only been recently that any work was undertaken to evaluate the wind effect. Thomas (39) examined the effect of wind on flame length, using wood crib fires for which measurements were made of burning rate, wind velocity, length of flame and angle of inclination from the vertical. The effect of wind on flames was also studied by Pipkin and Sliepcevich (40) and by Welker et al. (41) using burning liquid pools in a wind tunnel. Natural gas flames exposed to cross winds were studied by Putnam (42). Much work remains to be done to relate such correlations with a fire moving along a front in a real fuel system under the effect of wind, radiation and fire brand distributions.

To determine the conditions associated with a conflagration type mass fire, it is proposed to study this phenomenon to develop an analytical model. The experience gained by the development of the fire storm environmental model should prove to be of great assistance in this effort.

D. Determination of Debris Fire Behavior

1. Background

Debris fires may expose blast shelters causing heat transmission through the walls and roof. Probably of more

significance is the exposure of the shelter fresh air intake to carbon monoxide contaminated, hot fire gases, as well as heating the intake tube passing up through the debris pile. If the debris fire burns out in a comparatively short time (6 - 8 hours), the exposure may be no more serious than a fire in an adjacent building. However, if the debris fire has a long duration (a number of days) at moderate to high temperatures, then shelter occupants will be in danger, unless a self-contained life-support system is provided.

Very little information is available on the temperature and duration of debris fires. What information does exist pertains to the debris remaining from burned-out building fires, which bears little relationship to the debris from blast destroyed structures.

2. Approach

It is proposed to study the behavior of fires involving debris resulting from a nuclear attack. Selected occupancies and building construction types would be analyzed to evaluate the proportion by weight, volume and surface area of combustible and non-combustible materials in the structure and contents. Estimates of the weight per unit volume of debris piles would also be made. This information would then be used as an aid to describe typical debris piles. The volume, surface area and distribution of debris is related to the extent of fragmentation of the structure and its contents;

this in turn, is related to the location of the buildings with respect to ground zero.

After characterization of typical debris piles has been accomplished, the behavior of a fire in such a fuel bed can be studied experimentally, as follows:

a. Prepare and instrument a segment of a typical debris pile to measure fire duration, rate of burning and fuel bed temperature, as well as the temperature concentrations of carbon monoxide and oxygen in the gases directly above the fire. A sufficient number of debris pile segments would be burned to determine the effects of variation of debris pile density, pile thickness, and proportion of fuel on fire spread through a debris pile, rate of burning, duration, fuel bed temperatures, and temperature and carbon monoxide and oxygen concentrations in the hot gases immediately above the fire.

b. Set up an experiment to study the atmospheric diffusion pattern of typical fire gases. The fire gas distribution may be simulated by discharging into the atmosphere known gases, such as carbon dioxide, at known rates. Atmospheric samples would be taken at locations selected to provide information on the vertical and horizontal concentration profiles of the gases and thus measures of turbulent diffusivity. This experiment would be repeated under various conditions of wind velocity. This information would then be used to predict concentration profiles above large debris fires.

E. Exposure Correlations Through Effect On Materials

1. Background

Fire exposures are classified in Chapter IV as follows:

a. Distant Flame Exposure - characterized by transfer of heat to the shelter component due only to thermal radiation from a flame situated so as to avoid contact with the receiver.
b. Impinging Flame Exposure - characterized by transfer of heat to the shelter component due to the combined effects of thermal radiation and convection from flame in contact with the receiver.
c. Debris Fire Exposure - characterized by conduction heat transfer to the shelter component from a mass of hot or burning materials resting on or adjacent to the receiver.

It is desirable to be able to predict the responses of shelter components to these fire exposures from the results of a minimum number of standarized tests. This section describes experiments designed to evaluate the responses of shelter components to typical fire exposures to study the interrelations of time, temperature and rate of temperature change within components.

According to present practice, described in Section B of Chapter II, two fires, having different time-temperature curves, are said to be equally severe if the areas under the curves are the same for both. Further, this method of

comparison can produce accurate results only when the mechanism of fire damage is by pure heat conduction.

A basis for comparison of various types of exposures is given in Section A of Chapter IV, i.e., equivalent fire exposures produce identical time-variant temperature distributions within identical components, regardless of the mode (or modes) of heat transfer involved. This specification can be satisfied only if equivalent fire exposures produce identical heat flux into the surface of the barrier.

2. Scope

The scope of the work includes study of the effects on shelter components of the time, temperature, and rate of temperature change of the fire exposure, both with and without direct flame contact on the component. Homogeneous and heterogeneous fire barriers must be considered having both high and low insulative qualities. Inert materials, as well as those offering protection through ablative dehydration, and desorption processes, should be studied. It is suggested that the study be divided into two parts. The first deals with homogeneous specimens only and treats one-dimensional heat flow into specimens of relatively small sizes. The second deals with full scale (whole item or whole module of item) experiments on both homogeneous materials and heterogeneous materials, such as reinforced concrete, cellular and block assemblies.

3. Approach

For the small scale experiments, the specimens would be insulated at the edges, mounted on a suitably constructed furnace, and subjected to a soft flame source to represent the impinging flame exposure conditions. Measurements would be made of the heat flux input, temperatures at the exposed surface, unexposed surface and at intermediate points, as a function of time. Similar specimens would be subjected to a suitable thermal radiation source designed to represent flame exposure; measurement of flux and temperature for these specimens would be made in a similar manner.

For some specimens the flux input can be monitored to give an exposed surface temperature following the ASTM E 119 Standard Time-Temperature Curve. Also, conditions at the unexposed surface of the specimen can be varied to include uninsulated and well-insulated surfaces. The time to reach some pre-determined unsafe temperature condition on the unexposed surface can be obtained from these results

The specimens would be chosen from materials having the following general properties:

1. Noncombustible materials, containing no water, either combined or uncombined, so that heat transfer would be by pure conduction At least one specimen should have a relatively large thermal conductivity, while another should have relatively good insulating qualities.

2. Noncombustible materials containing water in some form, so as to impart the effects on heat transfer resulting from dehydration and desorption.
3. Materials having properties which influence heat transfer characteristics by ablation processes.
4. Combustible materials, such as wood, which influence heat transfer characteristics by dehydration, desorption, and pyrolysis processes.

The experimental results of several samples selected from the above kinds of materials should be compared; conclusions should be drawn regarding the interrelation of time, temperature and rate of temperature change within the specimens. The influence of the various modes of heat transfer on the time-temperature effects within shelter components should then become more apparent.

The second group of experiments on both homogeneous and heterogeneous materials would be conducted on a large scale, similar to that used for ASTM E 119 methods of test. These experiments would be designed to extend the results of the small-scale experiments to specimens approaching real shelter components. The complexity of the full-scale experiments will be determined to a large extent by the degree of simplicity with which the small-scale tests can be correlated. It is believed that the selection of specimens for these experiments should await the results of the small-scale tests.

As a result of the combined series of experiments, it is expected that conclusions can be drawn regarding equivalent fire exposures, and the number of standardized tests required to predict the responses of shelter components to the various fire exposures.

F. Effects of Restraint on Fire Tests

1. Background

Fire in a building generally may be expected to produce large forces of expansion in localized areas. Therefore, when the member or assembly is isolated from the structure to evaluate its fire resistance, some form of restraint must be utilized. Restraint may be defined as a representation of the influence exerted by the surrounding structure on an individual component. The use of restraint in fire testing is made in an attempt to simulate the forces opposing expansion in a real structure. In development of the ASTM fire test, complete restraint was chosen in preference to none at all. Either alternative can be misleading. Unrestrained homogeneous constructions may only expand under heating and then cool to about the original state. However, unrestrained composite structures may pull apart through unequal expansion, where they would not under the restraining influence of an actual building. Full restraint testing also can provide deceptive results. The restraining frame may support significant portions of the loading intended for the test member, thus

inhibiting its failure. To the other extreme, forces greater than possibly accommodated in most actual constructions can bring premature failure from shear type spalling. Therefore, since neither lack of restraint, nor complete restraint reasonably well represents the opposing forces of a building to the thermal thrusts developed by fire exposure, a determination of realistic partial restraint is necessary.

2. Scope

The objective of an experimental study of restraint should be the determination of the reaction of a structure to expansion forces applied from within. Part of this reaction will be angular distortion in vertical planes (folding at the frame junctions), such as would be expected from externally applied horizontal forces (wind, earthquake). The remainder of the reaction is in the horizontal plane (or adjacent planes) subjected to localized expansive forces. This latter reaction probably will not exist where these forces are applied near the building perimeter. Thus, the expected range of force resistance in any given structure, being a combination of the above two influences, will vary within the building; also, variations will be expected among building construction types.

3. Approach

With the above considerations, a restraint experimental study should consist of the following three phases:

a. Determination of the structural resistance to

internally applied forces, by making physical destruction tests of steel and concrete buildings scheduled for demolition. By applying horizontal force on the edges of a floor at a central shaft, the total resistance of both the floor slab and of the structural frame can be found. With a similar test at an outside corner, the frame resistance alone may be measured. This would establish the range of restraint which may be applied to fire testing for the building types examined.

b. Small scale tests with unconfined horizontal construction assemblies should be made in order to verify that mechanically induced forces applied from the center, are commensurate with isolated thermally induced forces similarly applied. In this study, the rate of heat application should be observed as it effects this relationship.

c. The effectiveness of predictions based on the parameters developed from a. and b., should be determined by performance in two full scale fire experiments, using representative constructions.

VII. CONCLUSIONS

1. Under attack conditions, a shelter cannot be evacuated to a location of safety during fire exposure, public fire fighting cannot be expected, and fire fighting by shelter occupants will be severely limited by the existence of radioactive fallout, as well as by a shortage of water. Therefore, in regard to resistance to the effects of fire exposure, the requirements for shelter components are different from those of building components for peacetime usage.

2. Present methods of fire tests of building construction and materials, door assemblies, and window assemblies are adequate in their techniques for developing the performance of components exposed to fire. In this regard, the test procedures need not be verified, largely due to the fact that the tests are conducted by exposure of a full scale module of the component under study.

3. Present fire test facilities can be used for the fire test rating of shelter components, subject to certain modifications pertaining to specimen restraint and to the evaluation of the flow of gases from the fire side to the shelter side of the component under test.

4. The present practice of using one standardized fire exposure to rate all building components is desirable. For the purpose of rating shelter components, this practice should

be followed only if a suitable method can be devised to translate test results from one exposure to apply to all other types of exposures. In any case, it is important to be able to predict the responses of shelter components to the four basic types of fire exposures from the results of a minimum number of standardized tests.

5. Success of the shelter component rating system depends upon the use of the proper input parameters pertaining to the various fire exposures. For this purpose the following research tasks should be accomplished:

a. Study the behavior of enclosure fires involving various fuel loads, and fuel distributions, combined with a variety of degrees of ventilation. The fuel load-ventilation extremes of fire conditions should be examined to identify the fire conditions important to the rating of shelter components.

b. Develop the information needed to evaluate the flow of fire gases through a component into a shelter exposed to conditions in a shaft or a corridor at some distance from a fire.

c. Develop the information needed to more clearly define a mass fire type of exposure, including duration, effective exposure temperature, and the rate of spread of a conflagration.

d. Study the behavior of debris fires as they pertain to the exposure of shelter components, including the fire duration, rate of burning, fuel bed temperatures, as well as the temperature and concentrations of carbon monoxide and oxygen in the hot gases directly above the fire, and downwind from the fire.

e. Correlate the four basic types of fire exposures to provide a basis for comparison of their effects on shelter components. Each exposure should be defined by a heat flux versus time curve.

f. Perform an experimental study of restraint to determine the reaction of a real structure to expansion forces applied from within. With this information, more realistic fire exposure tests of shelter components can be performed.

6. In regard to the results of fire exposure tests of shelter components, the following should be recognized:

a. The ratings for shelter components would be published for each exposure condition. In this manner the user is relieved of the responsibility of proper interpretation from a single set of fire test results.

b. The length of a test on any given shelter is determined by the duration of the type of exposure for which the component is to be rated.

c. The test results should be presented in graphical

form. Shelter component test results do not lend themselves to being reported as a single-point value.

d. Certain shelter components may permit the flow of gas from the fire side to the shelter side prior to fire exposure. This information should be reported.

e. Limitations on heat transmission by shelter components depend largely on the thermal design of the shelter. The rating of shelter components cannot be made solely on the basis of temperature rise on the unexposed side. Shelter components must be chosen so that the maximum overall heating rate for the shelter is not exceeded.

f. The value of the unsafe temperature on the unexposed side of a shelter component is not an end point in a fire test. This value may be different for different materials stored within the shelter, and the manner in which they are stored. Also, the location and use of any given component may determine its selected maximum shelter side temperature.

g. The collapse time of a shelter component is an end point in a fire test.

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APPENDIX A

GAS-CONTAMINATION RELATIONSHIP FOR SHELTER AREAS

Consider the flow of a contaminating gas-air mixture through a barrier into a shelter of volume V during a time τ. Assume that, as the mixture reaches the shelter side of the barrier, it is distributed instantaneously and uniformly throughout the volume V. Assume also that the differential pressure across the barrier remains constant during flow; this requires that, as a certain quantity of contaminating gas-air mixture reaches the shelter side of the barrier, an equal quantity of shelter atmosphere instantaneously leaves the shelter. The volumetric rate, Q is the rate of influx into the shelter and the rate of air leakage from the shelter.

Let the concentration (expressed as a volume fraction) of the contaminating gas on the fire side of the barrier be represented by X_f and that on the shelter side by X_s. Then the quantity of contaminating gas flowing with air into and out of the shelter in time $\Delta\tau$ is given by the relations,

$$\text{Quantity In} = X_f \, Q \, \Delta \tau \tag{A1}$$

$$\text{Quantity Out} = X_s \, Q \, \Delta \tau \tag{A2}$$

Then the net increase in quantity of contaminating gas in the shelter is given by the difference between the Quantity In and the Quantity Out, as follows:

$$V\Delta X = X_f \, Q \, \Delta\tau - X_s \, Q \, \Delta\tau \qquad \text{(A3)}$$

where

ΔX = The change in concentration of contaminating gas in the shelter during time $\Delta\tau$

This leads to the following differential equation

$$dX = \frac{X_f - X_s}{V} \, Q d\tau \qquad \text{(A4)}$$

which can be integrated as follows:

$$\int_o^{X_s} \frac{dX/X_f}{1 - X_s/X_f} = \frac{1}{V} \, Q \int_o^{\tau} d\tau \qquad \text{(A5)}$$

$$\tau = - \frac{V}{Q} \, \ln(1 - \frac{X_s}{X_f}) \qquad \text{(A6)}$$

$$X_s = X_f \, (1 - e^{\frac{-\tau}{V/Q}}) \qquad \text{(A7)}$$

To represent properly the effects of change in contaminating gas concentration with time, Eq. A7 can be integrated with respect to time with the following results:

$$\int_o^{\tau} X_s \, d\tau = X_f \left[\tau + \frac{V}{Q}(e^{\frac{-\tau}{V/Q}} - 1) \right] \qquad \text{(A8)}$$

In utilizing this derivation, it is assumed that the shelter is being contaminated by carbon monoxide from fire gases. Haggard and Henderson (8) formulated the toxic properties of carbon monoxide in terms of the product of the time of exposure and the concentration ($X_{co}\ \tau_c$).

$X_{co}\tau_c$ (ppm - hr)	$X_{co}\tau_c$ (% - min)	Effect
300	1.8	No perceptible effect
600	3.6	Just an appreciable effect
900	7.2	Headache and nausea
1500	9.0	Dangerous

By substitution of any one of the above values into Eq. A8, the time at which that specific effect would occur in a given fire shelter situation can be evaluated.

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13 ABSTRACT

In this study fire tests for the purpose of rating structural components of blast shelters and fallout shelters are considered. Existing fire test procedures for building construction and materials, door assemblies, and window assemblies are analyzed to determine how results from these tests may be applied toward the development of a system for rating shelter components.

Shelter component performance requirements in regard to heat transmission, smoke and toxic gas build-up in shelter areas, and fire spread and structural collapse are described.

Fire exposures for the rating of shelter components are described and classified according to their characteristic modes of heat transfer. The sources of these exposures, described as exposures from fire within the shelter building, from fire in individual nearby buildings, from mass fire, and from debris fire, are analyzed and interim data presented on exposure severity. A useful concept for the comparison of fire exposures, based upon their effects on each type of component, is defined.

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The approach used in existing fire test methods was found to be compatible with shelter component testing, provided furnaces are equipped with gas collection systems. Problems involving restraint of test specimens, encountered in existing test methods, persist in shelter component testing. An interim approach for the modification of existing restraining methods is recommended. Suggestions are made regarding the method of reporting results of shelter component tests.

Verification experiments are described, the completion of which would provide the additional input data needed for the fire test rating of shelter components.

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